Groundwater recharge and travel times in the sandy regions of the Netherlands

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VRIJE UNIVERSITEIT

GROUNDWATER RECHARGE AND TRAVEL TIMES IN THE SANDY REGIONS OF THE NETHERLANDS

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor aan
de Vrije Universiteit te Amsterdam,
op gezag van de rector magnificus
prof.dr E. Boeker,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der aardwetenschappen
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door

Cornelis Roelf Meinardi

geboren te Groningen

Promotor	: prof. dr J.J. de Vries
Copromotor	: prof. dr ir C. van den Akker
Referent	: prof. dr ir R.A. Feddes

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PREFACE

Preface

The soil is both a familiar and a mysterious entity to us. It is familiar because our daily lives are strongly connected to the soil. I am myself deeply rooted in a farmer's tradition of tilling the soil to earn a living. In a way, this study was a means of continuing this tradition. The mysterious features of the soil are related to the hidden character of its deeper layers, which can only be perceived with great physical efforts. The Dutch tradition of down-to-earth scientific research, expressed by the adagium of Simon Stevin,

'Wonder en is gheen wonder'
(Mystery is no miracle),

was for me an incentive to investigate this mysterious character of the soil.

The complex investigations reported in this document could never have been carried out if I had not had the support of institutions, colleagues and friends. I want to express my sincere thanks to all of them for assisting me in this work. In fact, the investigations covered such a long period of time and so many persons participated in them that the danger of forgetting somebody who has contributed to the results is great. Please forgive me for any oversights.

To start with, the final form of this thesis is largely due to Professor dr J.J. de Vries, the first promotor. He stimulated me to start working on it. All along the way he has given critical commentary on my writing in a pleasant and positive way, thus clearly improving the original version. My co-promotor, Professor dr ir C. van den Akker, has built a singular career, beginning as my apprentice, developing into a highly valued colleague and now functioning as a serious mentor. The remarks of Professor dr ir R. Feddes, the referee, were also greatly appreciated.

A number of persons have read the whole manuscript. The man to whom I am greatly indebted for introducing me to hydrological research, Mr G. Santing, has read it in his own precise way, so well-known to me. Dr S. Jelgersma advised me on geological matters in a comprehensive manner, just as she has done for more than 20 years. Also, Mr E. Romijn, my colleague for many years, shared in the task of commenting on the complete document. I am obliged to Mr L. Kohsiek for carefully reading the full manuscript and passing on comments, especially those related to the structure of the document.

The basic elements of the study were formed from part of the RIVM activities in the then new field of environmental research. It was my pleasure to have taken part in the discussions defining the direction in which the necessary efforts should go and then carrying them out. The project on the occurrence of nitrogen compounds in Dutch soils, enthousiastically managed by Mr W. van Duijvenbooden, has become a cornerstone of the present study. I thank Mr W.J. Willems, the stimulating co-ordinator at the Directorate General of Environment. The application of GIS facilities, now normal at RIVM but first initiated by Mr N.D. van Egmond, formed the perfect final stage of my activities. The whole RIVM institute has put the confidence in me to tie all the loose ends into the present study. Data obtained from the provincial monitoring network in Gelderland were kindly provided by Mr S. Hoogveld.

In all the now integrated parts of the study, I have been supported by many colleagues. I discussed the basics of regional and national considerations on the groundwater situation with Wennemar Cramer. Henk Kool provided the set-up for the RIVM tritium analyses, elaborated and largely carried out by Hetty Mesters. Jan van der Valk assisted not only in the fieldwork, but also in the interpretation of data. The results were discussed in meetings with Professor dr W.G. Mook. A large amount of the fieldwork was done in a close and always pleasant co-operation with Leo Boumans. Many methods, leading to efficient operations in the field, were discussed with Dirk Wever. The fieldwork was prepared and often also carried out by my colleagues, Ruud Jeths, Wim Post and Hans van Maaren. The RIVM 'Vervoersdienst' brought us and our instruments to the most remote places.

The instrumentation and the start of my geo-physical activities have been based on inspiring discussions with Dr W. Geirnaert of the Free University of Amsterdam, with Mr R. Boekelman of the Technical University of Delft giving valuable advice. The set-up of the sedimentological studies was most pleasantly discussed with Dr R. Boersma of Utrecht University, who also directed the activities of his students, C. Verhoeven, B. Kerkhof, M. van Hemert and A. de Jong. The sedimentological and accompanying investigations in Best were done in a close co-operation with Arie Obdam, Loes Gerringa and Jos van Alphen. The hydrological fieldwork on the investigated farms was carried out by the students M. de Nijs and M. Heuvelink. The investigation in the Veluwe region was done in co-operation with Utrecht University by the students P. Kaasenbrood, M. Mennen, G. Scheibe and L. Stax after discussions with Dr C. Schouten. The use of multi-layer sampling techniques was strongly promoted and applied as well by my former colleague, Gerrit Krajenbrink, as part of his co-operation in the activities.

After the fieldwork came the calculations, for which support was offered most generously by my retired colleague, Gijs Bruggeman, who made available the mathematical treatment of that part of groundwater flow I was interested in. My friend, Ed Veling, helped me to solve the same type of problems numerically. The regional representation of precipitation and actual evapotranspiration was amply discussed with Gerard van Drecht and Gé van den Eertwegh, who also elaborated on the subject. The final data treatment, carried out in a GIS environment, was initiated by Theo Thewessen. Monique Bollen did an admirable job in elaborating the data and presenting the results in the form of maps.

Ruth de Wijs carefully edited the final text, patiently enduring my layman's remarks on the English language. André Berends and Marga van Oostrom provided the layout of text and figures, all resulting in the splendid document you have before you.

The most important environment for the elaboration of this document was the home one. Thank you, Liesbeth, Marieke, Jantien and Roelf, for accepting the fact that I was busy during so many days that were also suitable to more enjoyable activities.

This thesis is dedicated to my father Jan Meinardi †, who educated me in the liberal and rational way of thinking which, I hope, still forms the basis of my actual work.
't Is muite weerd west pa.

Bilthoven,
16 May 1994
Cornelis Roelf Meinardi

SAMENVATTING

De bodem bestaat uit het geheel van de onder het aardoppervlak aanwezige vaste delen met de zich daarin bevindende vloeistoffen, gassen en organismen. Grondwater is dus een onderdeel van de bodem. Verschillende soorten van vervuiling bedreigen de bodem van Nederland. Te onderscheiden zijn puntbronnen en diffuse bronnen van verontreiniging. Puntbronnen kunnen ernstige lokale effecten hebben, maar de gevolgen van een diffuse vervuiling zijn in grotere gebieden merkbaar, zodat de totale aantasting van de bodem groter kan zijn. Een diffuse verontreiniging is bovendien moeilijker terug te dringen. Het grondwater speelt een belangrijke rol. Diffuse verontreinigingen grijpen meestal aan bij het maaiveld en verdere verbreiding vindt vaak plaats door middel van transport met het grondwater. Hydrologisch onderzoek kan uitspraken doen over de snelheid van de grondwaterstroming, die ten grondslag ligt aan het transport van stoffen in de bodem. In deze studie gaat het voornamelijk om de vertikale beweging van het grondwater.

Bij diffuse verontreiniging is vooral vertikaal transport belangrijk en die is afhankelijk van de neerwaartse snelheid van de stroming van het grondwater. In dit opzicht is er een groot verschil tussen de klei- en zandgebieden van Nederland. In zandlagen stroomt het grondwater meestal sneller dan in kleiige afzettingen. Bovendien reageert een zandige bodem anders op een verontreiniging in de zin dat minder natuurlijke verwijdering door processen in de bodem plaats vindt. Tenslotte is ook de belasting met meststoffen in het algemeen het grootst in de zandgebieden. Daarom heeft vooral de stroming van het grondwater in de bodem van zandgebieden aandacht gekregen.

De vertikale stroming van het grondwater wordt voornamelijk veroorzaakt door de aanvulling van het grondwater door de neerslag. De snelheid van deze beweging is vrijwel niet rechtstreeks te meten en ook de aanvulling is niet op een directe manier te meten. De neerslag is wel te bepalen, maar de reductie van de aanvulling als gevolg van de verdamping (vooral de transpiratie door planten) kan alleen worden geschat op basis van de onderliggende grootheden. Een datering van het grondwater met behulp van het gehalte aan tritium is daarom een nuttig hulpmiddel. Tritium is een natuurlijk isotoop van waterstof, waarvan de concentratie in de neerslag per jaar varieert, zodat de gehalten in het grondwater kenmerkend kunnen zijn voor het jaar van herkomst. Tritium reageert nauwelijks op een transport door de bodem, het heeft de kenmerken van een "ideale tracer". Als de reistijden van het grondwater bekend zijn door middel van dateringen met tritium, dan volgen daaruit aanduidingen over de snelheid van de stroming en dus ook over de aanvulling van het grondwater.

Uit beschouwingen over de hydrologie van het ondiepe grondwater in de zandgebieden van Nederland volgen een aantal algemene aanwijzingen over de opzet van het onderzoek:

1. De werkelijke snelheid van het grondwater is in veel gebieden in de orde van grootte van 1 meter per jaar, tenminste als geen andere wijze van afvoer optreedt, bijvoorbeeld door ondiepe drainage;
2. Voordat het grondwater de verzadigde zone bereikt is het tenminste op jaarbasis gemengd, zodat geen seizoensvariaties optreden en bovendien is de grootte van de stroming vrijwel constant in de tijd.
3. In gebieden waar oppervlakkige afvoer (afvoer door greppels en door drainagebuizen) een deel van de neerslag verwijdert, vormt de datering van grondwater vrijwel de enige manier om de vertikale snelheid te bepalen.
4. Als het intrekgebied van het grondwater inhomogeen is met betrekking tot de verdamping, dan is de situering van waarnemingsputten en de lokale horizontale stroming van het grondwater van groot belang bij de interpretatie van de reistijden.

Onderzoeksmethoden

Het onderzoek van de Nederlandse zandgebieden is opgebouwd van fijn naar grof: De resultaten van veldonderzoek op verspreide locaties zijn samengevat tot regionale overzichten. De conclusies uit de regionale studies lagen vervolgens ten grondslag aan een landelijk beeld. Belangrijke onderdelen van het veldonderzoek waren een sedimentologische analyse van grondmonsters, een geofysische verkenning van de lokatie en hydrochemische beschouwingen over de samenstelling van het grondwater. Ongestoorde grondmonsters vormden de basis van het sedimentologisch onderzoek. Bij de lokatie te Best zijn de monsters verkregen uit twaalf door een boorfirma gemaakte boringen volgens het Ackerman systeem, die in een stramien van 40 bij 40 meter waren geplaatst en die tot een diepte van 30 meter gingen. Op tien plaatsen elders in het land zijn boerderijen onderzocht op een eenvoudiger manier. Een eigen veldploeg heeft boringen gemaakt tot een diepte van 8 meter met de Van der Staay suction corer. In beide gevallen zijn echter lakprofielen gemaakt van de overlangs doorgesneden boorkernen die vervolgens sedimentologisch zijn geanalyseerd. Het resultaat bestond uit een gedetailleerde beschrijving van de bodemlagen en een schatting van hun ruimtelijke verbreiding.

De geofysische methoden waren vooral gericht op een verkenning van de ondiepe ondergrond met inbegrip van de samenstelling van het grondwater. De toegepaste methoden waren geo-electrische oppervlakte-metingen, uitgevoerd met een ABEM Terrameter en een Barker kabel en electromagnetische verkenningen met de Geonics EM-31. Met name de geleidbaarheid van het grondwater kwam tot uitdrukking bij deze metingen. Een belangrijke conclusie is dat het effect van verontreiniging duidelijk tot uitdrukking komt in de metingen. Geofysische onderzoek is zeer geschikt om op een snelle manier een eerste indruk te verkrijgen van de verspreiding van een verontreiniging.

Het verband tussen de aanvulling en de chemische samenstelling van het grondwater is voor een aantal gebieden onderzocht. Het onderzoek van de Veluwe bestond uit gedetailleerde studies van het grondwater op een aantal locaties van het door de sprengen afgevoerde (grond)water. Waarden voor de aanvulling van het grondwater volgden uit verschillende benaderingen, die onderling werden vergeleken. Bepalingen van de aanvulling van het grondwater die gebaseerd waren op beschouwingen over de indamping van regenwater bleken in overeenstemming te zijn met berekeningen van reistijden met behulp van tritiumgehalten in het grondwater en in het water van de sprengen. Ook schattingen op grond van neerslag en verdamping kwamen op vergelijkbare waarden uit.

Op andere lokaties was het mogelijk om grondwater met een afwijkende samenstelling te volgen in de bodem. De ligging van specifieke stroombanen kan hiermee worden ingeschat en daardoor was het ook mogelijk om een schatting te maken van de grootte van de horizontale en de vertikale componenten van de stroming. De berekende vertikale snelheid van de stroming resulteerde in een waarde voor de aanvulling van het grondwater.

Tritium als dateringsmethode voor grondwater

Tritiumgehalten in grondwater geven een aanduiding van de reistijden in de bodem door middel van een vergelijking van de in het grondwater gemeten gehalten met de verschillende gehalten in de neerslag in de loop der jaren. De maandelijkse gehalten in de neerslag zijn vanaf 1970 gemeten te Groningen door het Centrum voor Isotopen Onderzoek (CIO) en in Bilthoven door het RIVM. Vanaf 1980 tot 1990 is tevens op de twaalf meteorologische hoofdstations van het KNMI het tritiumgehalte van de neerslag bepaald. In het kader van de studie is een referentiereeks opgesteld die geldt voor Groningen. Aangehouden is dat de gehalten voor 1950 gelijk waren aan 5 TU. Verder is de reeks voor de periode van 1950 tot 1960 gebaseerd op meetgegevens van Ottawa, voor de periode 1960-1970 op metingen in de omgeving van Wenen en na 1970 op metingen te Groningen. Daarnaast heeft de bewerking van de gegevens uit de periode 1980-1990 van op verschillende plaatsen in Nederland gemeten tritium gehalten in de neerslag het verband opgeleverd tussen de waarden op een willekeurige plaats in Nederland en de reeks voor Groningen.

Voor een aantal plaatsen in Nederland zijn profielen samengesteld van het tritiumgehalte in monsters water die op dezelfde dag genomen zijn uit filters op verschillende diepte in een waarnemingsput. Een dergelijk profiel naar de diepte in het grondwater maakt een goede vergelijking mogelijk met de veranderingen in het tritiumgehalte van de neerslag in de tijd. Bij een aanvulling van het grondwater door de neerslag volgt het tijdstip van inzijging van het grondwater op verschillende diepten uit de vergelijking van beide grafieken. De onderlinge verschillen in reistijd geven de vertikale snelheid van het grondwater aan. Behalve een datering van grondwater kan bestudering van de tritiumgehalten ook aanwijzingen opleveren over de hydrologische situatie rond het waarnemingspunt, zoals het voorkomen van open water verdamping of het transport door oppervlakkige componenten van de afvoer. Van filters in waarnemingsputten van de landelijke en provinciale meetnetten voor de grondwaterkwaliteit zijn meestal slechts twee of drie gegevens beschikbaar over het tritium gehalte. Ook in dergelijke gevallen is een interpretatie mogelijk die echter minder nauwkeurige gegevens oplevert dan de beschouwing van een gedetailleerd tritiumprofiel.

Vijf illustratieve situaties

Vijf gedetailleerde studies in het oosten van Noord-Brabant hebben interessante conclusies opgeleverd over de bepaling van de aanvulling van het grondwater in verschillende situaties. Twee lokaties waren gelegen in landbouwpercelen (Venhorst en Best), twee andere lagen in een bosgebied (Rips en Vredepeel) en de vijfde lokatie lag naast het natuurgebied Griendtsveen, waar de beheerder opnieuw veengroei stimuleert. De waargenomen tritiumgehalten leverden in alle gevallen relatief nauwkeurig bepalingen op van de aanvulling van het grondwater. Het was daarbij echter wel nodig om een waarde voor de porositeit aan te nemen. Een vergelijking van de zo bepaalde waarden voor de aanvulling met waarden die uit andere methoden volgden, leverde een schatting op voor de porositeit van p=0.35. De regionale studies geven ook aan dat p=0.35, wat blijkbaar een goede benadering is voor de effectieve porositeit van zandlagen in de Nederlandse bodem.

Uit de interpretatie van de metingen in de onderzochte bosgebieden volgde dat de aanvulling van het grondwater sterk varieerde. Een bos is vaak inhomogeen in de zin dat het afwisselend zones met bomen en open plekken bevat. Bomen geven aanleiding tot een relatief grote verdamping die deels bestaat uit open water verdamping vanaf de kronen. Het effect is dat de gehalten aan zware isotopen in het grondwater toenemen ten opzichte van de oorspronkelijke gehalten in de neerslag (op de onderzochte locaties zijn behalve tritium ook de zware isotopen ^{18}O en ^{2}H in het grondwater gemeten). Bij open plekken is de verdamping juist relatief gering met als gevolg dat de lokale aanvulling van het grondwater groot is, maar ook dat de samenstelling van het grondwater anders is dan onder bomen. Vooral de metingen in het naaldbos te Vredepeel, waar een perceel bos werd gekapt tussen twee datums van monsterneming, gaven inzicht in het effect van open plekken op de aanvulling en de samenstelling van het grondwater in bosgebieden.

Het onderzoek van de lokatie naast het Griendtsveen was interessant omdat het bemonsterde grondwater aangevuld werd in een moerassig gebied. De aanvulling in de naast het monsterpunt gelegen zone waar het veen was afgegraven, was klein, zonder dat sprake was van een duidelijk effect van open water verdamping. De tritiumgehalten waren zelfs duidelijk lager dan de overeenkomende gemiddelde gehalten in de neerslag. De meest waarschijnlijke oorzaak is dat een sterke evapotranspiratie door phreatophyten de volledige neerslag in de zomer en tevens van delen van het voor- en najaar verwijdert, met inbegrip van de zware isotopen. Het iets diepere grondwater dat waarschijnlijk is geïnfiltreerd vanuit het niet verveende gebied, gaf wel duidelijk de invloed van open water verdamping aan, zoals bleek uit de waargenomen combinaties van de ^{2}H en ^{18}O gehalten.

De waarnemingen te Best hebben geresulteerd in op verschillende wijzen gemaakte schattingen voor de aanvulling van het grondwater. Schattingen op basis van de verspreiding van een lokale vuilpluim in de ondergrond kwamen overeen met de waarde die volgde uit de gemeten tritiumgehalten in het grondwater. De aanvulling van het grondwater is in beide gevallen ca. I= 110 $mm{\cdot}a^{-1}$. De schatting op basis van neerslag en werkelijke verdamping gaf een veel hogere waarde aan van ongeveer I=250 $mm{\cdot}a^{-1}$. Het verschil ligt waarschijnlijk in de oppervlakkige afvoer van een groot deel van de neerslag in de winter door of over de lagen, die liggen boven een ondiepe leemlaag van een grote uitgestrektheid (Brabantse leem). De konsekwentie van een kleinere aanvulling van het diepere grondwater is dat de reistijden groter zullen zijn. Behalve in delen van Brabant komt ook in Drenthe regelmatig een situatie voor waar in de ondiepe bodem een storende leemlaag aanwezig is (keileem of beekleem). In zo'n situatie moet dus rekening worden gehouden met langere reistijden in de bodem.

De situatie te Venhorst betreft het voor de Nederlandse zandgebieden normale geval van een aanvulling van het grondwater vanuit een landbouwgebied zonder dat storende lagen aanwezig zijn in de ondiepe bodem. Het langjarig gemiddelde neerslagoverschot bedraagt potentieel $P-E_p$=740-500=240 $mm{\cdot}a^{-1}$, waarin P de neerslag is en E_p de potentiële evapotranspiratie. Uit de tweemalig gemeten tritiumprofielen volgt een waarde van de inzijging van I=290 $mm{\cdot}a^{-1}$. Het verschil is verklaarbaar door aan te nemen dat de werkelijke evapotranspiratie E_a kleiner is dan de potentiële doordat de beschikbare hoeveelheid bodemvocht niet in staat is de benodigde hoeveelheid water te leveren voor een potentiële evapotranspiratie. Door de Werkgroep HELP (1987) zijn schattingen gemaakt van de gemiddeld voorkomende vochttekorten in verschillende gebieden die voor Venhorst goed overeenkomen met het geconstateerde verschil.

Regionale overzichten van de zandgebieden

De regionale overzichten van de grondwateraanvulling zijn gebaseerd op gedetailleerde bestudering van tien boerderijen en daarnaast op de tritiumgehalten die gemeten zijn in de filters van het Landelijk Meetnet Grondwaterkwaliteit. Voor het centrale zand-district en voor de kustduinen, waar geen onderzochte boerderijen liggen, zijn aparte beschouwingen opgezet om inzicht te verkrijgen in de aanvulling van het grondwater in natuurgebieden. Het landgebruik in de Nederlandse zandgebieden is overheersend landbouw. De potentiële verdamping van landbouwgewassen kan worden benaderd door de Penman open water verdamping of de Makkink referentie verdamping te nemen en die te vermenigvuldigen met de voor die gewassen geldende gewasfactoren. De neerslag volgt uit een bewerking van meetgegevens van het KNMI. De resultaten van het onderzoek op de tien proef-boerderijen en de meetnetputten (tritium gehalten) leiden eveneens tot de conclusie dat de werkelijke verdamping goed kan worden benaderd door uit te gaan van de schattingen van het vochttekort, zoals die door de HELP-studie worden gegeven. Met de beschikbare gegevens was niet na te gaan of de toename van het neerslagoverschot (ten opzichte van neerslag minus potentiële verdamping) een resultaat was van vochttekorten of van het toepassen van beregening. Beide factoren kunnen een ongeveer even grote vermeerdering van de aanvulling van het grondwater opleveren. Hieruit volgt dat de combinatie van de meteorologische gegevens verzameld door het KNMI en de uit de HELP-studie afgeleide gemiddelde vochttekorten een goede basis vormt voor een schatting van het neerslagoverschot op het landbouwareaal in de Nederlandse zandgebieden. Oppervlakkige componenten van de afvoer van het neerslagoverschot konden worden afgeleid uit de tritium metingen in gebieden waar een storende kleilaag aanwezig is in de ondiepe bodem, zoals in grote delen van Drenthe en van Noord-Brabant.

Het regionaal onderzoek van de Veluwe leverde waarden op voor de verdamping vanuit natuurgebieden. De verschillende hiervoor gebruikte methoden waren:

- Tritium metingen in het ondiepe grondwater van drie lokaties;
- Tritium metingen in het door de sprengen afgevoerde water;
- Analyses van de chemische samenstelling van het grondwater op zeven locaties;
- De chemische samenstelling van het door de sprengen afgevoerde water;
- Tritium gegevens van de putten van het Landelijk Meetnet Grondwaterkwaliteit;
- Tritium gegevens van de putten van het Provinciaal Meetnet Grondwaterkwaliteit;
- Een regionale en langjarige waterbalans van de Noord-west Veluwe.

De bepalingen van de aanvulling van het grondwater onder heidevelden resulteerde in een grote variatie in de uitkomsten. Dit komt waarschijnlijk doordat zeer verschillende gebieden onder de noemer "heideveld" zijn gebracht, bijvoorbeeld gebieden met zandverstuivingen, maar ook gebieden met een dichte grasachtige begroeiing. De verdamping vanuit beide soorten gebieden zal zeer verschillend zijn.

De schatting van de aanvulling van het grondwater in bosgebieden leidde wel tot overeenkomstige resultaten. Voor bosgebieden geldt dat de plaats van de metingen ten opzichte van met bomen beplante zones en open plekken belangrijk is voor de interpretatie van de aanvulling van het grondwater. Hierdoor is het verklaarbaar dat de interpretatie van metingen onder bomen lagere waarden opleverde voor de aanvulling dan de interpretatie van de samenstelling van het water van de sprengen, waarvan het intrekgebied meer open plekken heeft. Eenzelfde redenering geldt ook voor de putten van de diverse meetnetten die door hun grotere diepte water van verschillende herkomst kunnen opvangen. De gemiddelde aanvulling van het bemonsterde grondwater kan daardoor iets groter zijn. Algemene conclusies zijn:

1. De werkelijke verdamping van gebieden met een dichte bedekking met (naald)bomen op de Veluwe is bij goede benadering gelijk aan de Penman open water verdamping, dus $E_a = E_o$. In natte jaren is E_a zelfs iets groter dan E_o.
2. De gemiddelde verdamping van inhomogene bossen, met een relatief groot deel aan open plekken is minder dan de Penman open water verdamping. Voor de bossen van de Veluwe geldt gemiddeld dat $E_a = 0.9*E_o$.

De bewerking van de gegevens over het tritiumgehalte uit de meetnetten in andere bosgebieden resulteerde in het algemeen in hogere waarden voor de grondwateraanvulling dan gevonden werden voor het Veluwegebied. Een mogelijke oorzaak is dat de putten vaak geplaatst zijn op de overgang van bos en open plek (aan een bospad), waardoor de verdamping kleiner is dan gemiddeld. In het algemeen is als eerste benadering voor de Nederlandse bosgebieden aangehouden dat de voor de Veluwe bereikte conclusies ook gelden voor de andere bosgebieden.

De gemiddelde werkelijke verdamping van niet-beboste duingebieden met een natuurlijke vegetatie blijkt ongeveer $E_a = 500\ mm \cdot a^{-1}$ te zijn. Aangezien de open water verdamping langs de hele Nederlandse kust steeds een ongeveer constante waarde heeft, volgt hieruit dat bij benadering geldt dat $E_a = 0.7*E_o$. De variatie in de berekende waarden is echter groot, waarschijnlijk om dezelfde reden als genoemd is voor de heidevelden van de Veluwe. Bij de interpretatie van de gemeten tritiumgehalten bleek dat vaak rekening moest worden gehouden met een geringe aanrijking (0 tot 20%) in het grondwater in vergelijking met de gehalten in de neerslag, waarschijnlijk als gevolg van open water verdamping.

Enkele specifieke uitkomsten van het onderzoek

Uit de vergelijking van de tritiumgehalten in de neerslag met de tijd en in het grondwater met de diepte bleek dat vrijwel steeds een goede overeenkomst aanwezig is. De overeenkomst is minder goed voor grondwater dat in de jaren 1962-1965 is aangevuld door de neerslag. De in het grondwater aangetroffen tritiumgehalten zijn systematisch lager dan op grond van de referentie-reeks zou mogen worden verwacht. De bijzonder hoge tritiumgehalten die in die periode in de neerslag te Wenen zijn gemeten, mogen blijkbaar niet zonder meer naar Nederland worden geëxtrapoleerd. De overeenkomst tussen grondwater en neerslag is beter als de op basis van een literatuurstudie aangenomen gehalten voor 1962-1965 met ongeveer de helft worden verminderd. Met dit gegeven is een aangepaste referentie-reeks samengesteld. Vermoedelijk geldt ook voor de regionale factoren dat ze in het verleden andere waarden hadden dan thans. Door gebrek aan gegevens was het echter niet goed mogelijk om een eventueel verloop in de tijd van de regionale factoren aan te geven. Gezien de beschikbare gegevens die vooral van na 1970 dateren, is het belang van een aanpassing van de regionale factoren ook minder groot. Het geheel leidt tot de conclusie dat de aangepaste referentiereeks en de regionale factoren een goed beeld geven van de tritiumgehalten in de neerslag in het verleden op elke willekeurige plaats in Nederland.

De vergelijking van neerslag gewogen jaargemiddelden van het tritiumgehalte in de neerslag met gehalten in het grondwater van landbouwgebieden leverde een goede overeenkomst op, uiteraard wel met inachtneming van regionale effecten. Deze constatering vormt een ondersteuning van de uit een bewerking van gegevens van de neerslag gevonden regionale factoren voor het tritiumgehalte in de neerslag van Nederland. In natuurgebieden is vaak sprake van een aanrijking van de gehalten in neerslag voordat infiltratie in de verzadigde bodem plaats vindt, met als vermoedelijke oorzaak het voorkomen van open water verdamping. Voor de interpretatie van tritiumgehalten in het grondwater uit bosgebieden is het daarom gewenst om de waarden van de referentie-reeks, na toepassing van een regionale factor, nog eens met een factor 1.5 te vermenigvuldigen.

Voor de interpretatie van de waargenomen tritiumgehalten in het grondwater is uitgegaan van een op hydraulische gronden verondersteld patroon van stroming dat bepaald wordt door de waarde van de aanvulling en de dikte van het watervoerend pakket. Het feit dat in haast alle gevallen een goede interpretatie mogelijk was, geeft aan dat het veronderstelde patroon van stroming in het grondwater een goed beeld geeft van de in werkelijkheid optredende stroming. Dit patroon houdt in dat de stroming plaats vindt door de volledige dikte van het pakket van de Pleistocene afzettingen in Nederland, behalve in gebieden waar een serie dikke kleilagen het pakket verdeelt. Ook de overige waarnemingen, bijvoorbeeld die van de samenstelling van het water dat de sprengen van de Veluwe voedt, ondersteunen deze conclusie. Een volgend argument is dat ook in de monsters uit de filters op een diepte van 25 m van de meetnetputten heel vaak tritiumgehalten zijn gemeten die duiden op een continue stroming. De conclusie is dat de interpretatie van de in Nederland waargenomen tritiumgehalten in het algemeen geen steun geeft aan een opdeling in geneste aquifers, zoals die worden verondersteld in de systeem-analytische benadering van de stroming van het grondwater, zoals die onder andere door IGG-TNO wordt voorgesteld.

Aspecten van de bodemkwaliteit

In veel van de onderzochte lokaties is uitvoerig onderzoek gedaan naar de samenstelling van het grondwater. De metingen op de onderzochte boerderijen, waar op basis van tritium profielen de aanvulling van grondwater bekend is, leiden tot de volgende conclusies:

1. De uitspoeling van stikstof naar het freatisch grondwater vindt vooral plaats in de vorm van nitraat. Van de totale belasting spoelt meestal tussen 10 en 20% uit.
2. De uitspoeling kan in de meeste gevallen bij goede benadering worden voorspeld met een relatief eenvoudig evenwichts-model (NLOAD). De diepte van het grondwater onder maaiveld is de belangrijkste factor voor de optredende variatie.
3. Seizoensfluctuaties zijn vrijwel afwezig in het nitraatgehalte van het grondwater in de eerste twee meter onder de grondwaterspiegel.
4. Bij stroming door ondiepe verzadigde lagen treedt een additionele verwijdering van nitraat op die gemiddeld ongeveer 50% bedraagt, maar die een grote variatie heeft.
5. In twee gevallen zijn veel lagere nitraatgehalten aangetroffen dan werd verwacht. Een verklaring voor dit verschijnsel is niet eenvoudig te geven.

Beschouwingen ten aanzien van de samenstelling van het natuurlijke water op de Veluwe geven aan dat de neerslag de meeste van de in het grondwater voorkomende verbindingen aanvoert. De samenstelling van het grondwater volgt bij goede benadering uit de hoedanigheid van de neerslag bij toepassing van de voor dat grondwater geldende indampfactoren, echter met enkele uitzonderingen. Voor het sulfaatgehalte moet met een extra toevoer door droge depositie van ca. 3 $mg \cdot l^{-1}$ worden gerekend. De door de regen aangevoerde stikstofverbindingen worden voor een groot deel (ca. 60%) verwijderd door denitrificatie in de ondiepe bodem.

GIS bewerking van de aanvulling en bepaling van de reistijden

Het verband tussen het neerslagoverschot, meteorologische factoren en eigenschappen van de bodem wordt ondersteund door de interpretatie van de gehalten aan tritium. Bovendien is per gebied een schatting gemaakt van het mogelijk voorkomen van oppervlakkige componenten van de afvoer van het neerslagoverschot. De combinatie van deze factoren bepaalt de aanvulling van het grondwater. De waarden van de maatgevende grootheden zijn aanwezig in de vorm van digitale data-bestanden. Een verwerking met behulp van GIS-methoden levert een waarde op voor de grondwateraanvulling op elke willekeurige plaats in het zandgebied van Nederland. De aanvulling van het grondwater brengt een vertikale stroming op gang, waarbij de relatie tussen reistijd, bodemopbouw en mate van aanvulling uitgedrukt kan worden met de formule:

$$t=(p*D/I)*\ln[D/(D-z)]$$

Toepassing van deze formule vereist waarden voor de porositeit (daarvoor bleek p=0.35 te gelden); voor D (de dikte van de aquifer, afgeleid uit algemene geologische gegevens) en voor I (de berekende aanvulling). GIS-methoden zijn gebruikt om de reistijden te bepalen van grondwater op diepten van respectievelijk z=5 m; z=10 m; z=25 m, waarin z de diepte onder de grondwaterstand is. De beschouwde diepten komen overeen met de filterdiepten van de diverse meetnetten.

SUMMARY

General aspects

The present study gives an account of local and regional investigations on groundwater recharge and the resulting transport of water and solutes through the subsurface of sandy soils in the Netherlands for the purpose of establishing the connection with soil quality deterioration. Soil contamination by diffuse sources of pollution is a serious problem in the Netherlands, implying a growing interest in the rates of downward percolation and in residence times of water in the soil. Sandy regions in the Netherlands run the highest risk of diffuse pollution, not only because sandy soils are the most vulnerable to pollution, but also because the fertilizer and excess manure load is the highest in these areas. The methods used to determine the patterns in shallow groundwater flow for tracing the effects of soil contamination can be characterized as environmental hydrology.

Pollution at the land surface is transported by groundwater flow in vertical and horizontal directions. Direct measurements of groundwater flow are, in most cases, hardly possible and theoretical considerations often lack reliable data. The downward flow is related to groundwater recharge; however, also the methods to quantify groundwater recharge, which are based on a determination of excess rainfall, do not always yield accurate results. Dating shallow groundwater on the basis of its tritium content represents a relatively simple and direct means of determining the rate of downward percolation. In doing so, shallow groundwater flow has to be considered in the general context of the hydrological situation, especially of the shallow subsurface. Important aspects arising from a general review of the hydrological situation in the sandy regions with regard to the set-up of investigations of groundwater recharge and travel times are the following:

- Methods should be used which are well suited to assessing downward velocities in the order of magnitude of 1 $m \cdot a^{-1}$, being initiated by a groundwater recharge which is evenly distributed over the year.
- Especially where surficial discharge components remove a part of the rainfall excess, the determination of the age of groundwater represents the most reliable way to estimate the amounts of groundwater recharge.
- When investigating areas with an inhomogeneous vegetation, both the position of the observation wells and the direction of the horizontal groundwater flow in relation to the local topography should be taken into account.

Exploration methods

The methods used to describe the shallow soil and its groundwater include sedimentological analyses, geophysical surveys and hydrochemical tracer studies. Sedimentological investigations as part of environmental soil studies were realized in two ways. At one location (Best), a detailed study, based on expensive drillings by the Ackerman system, was carried out. The system yielded high-quality lacquer peels of the cores. A relatively complicated method to collect soil samples was chosen because the sediments were deposited in a geologically long period under varying conditions, leading to a complex soil structure. The second, simpler set-up was used at the reconnaissance of the shallow subsurface of 10 farms investigated. The sedimentological analyses were based on drillings made manually using the Van der Staaij suction corer. The resulting laquer peels were of a lesser quality, but nevertheless proved to be useful. The sedimentological analysis was based on a description of structures, discernable at the lacquer peels. These methods led to an understanding of the hydrological behaviour of the shallow soil at the Best location, including a quantification of horizontal and vertical flow rates. The test farm studies resulted in better insight into the nature and genesis of the subsurface, implying conclusions relevant to the reaction of the soil to the percolating high nitrogen loads.

Geophysical methods were used to identify the structure of the soil, as well as the occurrence and the distribution of groundwater with different conductivities. The sites of roughly 5 to 50 ha investigated were fully covered by electromagnetic (EM-31) observations, which were interpreted with the help of one or more geo-electrical arrays, executed by a Terrameter and a BGS-128 multi-core cable. These explorations made clear that the effects of pollution on groundwater composition are often detectable with geophysical measurements. Consequently, geophysical methods constitute a quick and relatively easy means to trace pollution.

The relation between groundwater recharge and the resulting groundwater composition has been elaborat-

ed in the context of the present study. The investigations at the Veluwe region consisted of five detailed groundwater studies and a survey of stream discharges (the 'sprengen') draining the groundwater. Methods based on the condensation of chemical elements during the transfer from precipitation to groundwater resulted in values for groundwater recharge in agreement with estimates of precipitation and actual evapotranspiration from meteorological data. These figures also correspond to infiltration values based on tritium data. In other areas investigated, various sources of pollution were active, resulting in a varying groundwater composition. The polluted plumes in the groundwater of Vredepeel forest and at the Best site were detected and could be used as tracers to assess groundwater flow patterns, resulting in estimates of the horizontal and vertical components of groundwater flow.

Groundwater dating

The interpretation of the tritium levels in groundwater in the sense of 'groundwater age' was based on a comparison of the vertical variation of tritium in the soil and the tritium fluctuations in rainfall over time. A reference series was composed for average annual tritium levels in Groningen precipitation covering the full period up to 1991. Before 1950, the tritium levels in rainfall were about 5 TU, a value representing the natural background. After 1950, the reference series was based on an extrapolation of Ottawa data for the period 1950-1960, on Vienna data for 1960-1970 and thereafter on local measurements. The analysis of rainfall levels for different locations resulted in regional factors, indicating the average differences between tritium in the precipitation in Groningen and at 12 other meteorological stations in the Netherlands.

Tritium profiles provide a good basis for interpreting the age of groundwater where the soil is recharged by precipitation. The age is determined by matching trends in rainfall and in groundwater tritium data. Apart from showing groundwater dating, the evaluation of tritium levels can also indicate specific hydrological situations, like the effects of open water evaporation or the seasonal incidence of surficial runoff. In contrast to the detailed investigations, only 2 or 3 observations per well are available in the national and provincial groundwater quality monitoring networks. Appropriate techniques were developed for the interpretation of the few observations from individual monitoring wells.

Detailed field studies

Five detailed studies were carried out to support the set-up of the local surveys: two investigations of the soil on agricultural lands (Best and Venhorst), two in forest areas (Rips and Vredepeel) and one near a swamp (Griendtsveen). The determination of the actual velocity of downward groundwater flow was mainly based on tritium profiles.

The calculated values of the vertical velocity had to be multiplied by the porosity to determine the groundwater recharge. The results could be compared to values derived by other methods. In Best, the vertical flow could be determined by hydrochemical tracer studies. A comparison with the tritium-based vertical percolation resulted in a porosity value of $p=0.35$ or slightly more. At Rips, the transition in groundwater quality caused by differences in vegetation yielded an estimate of the vertical velocity. Comparison with tritium data resulted in a porosity value of $p=0.35$. An effective porosity of the subsurface by good approximation of $p=0.35$. follows from the detailed investigations and the regional surveys.

The groundwater recharge of forest areas varied widely, depending on the situation of open spaces and forest lanes near the observation well. A variable part of the forest evapotranspiration consists of open water evaporation from rainwater intercepted by the canopy. Tritium levels are affected by an enrichment with tritium (and other heavy isotopes). In the detailed investigations ^{18}O and ^{2}H levels in groundwater were also determined. Especially the Vredepeel investigation gave insight into the effect of open spaces in a forest area.

The Griendtsveen study illustrated the hydrological conditions prevailing in swampy areas. The relatively deep groundwater was recharged at the remnants of a raised bog, which are present at a distance of 300 m to the east. The ^{18}O levels in deeper groundwater indicated the occurrence of open water evaporation during recharge, probably from the large open water surfaces in the non-excavated area. The groundwater recharge determined had a relatively low value of roughly $I=100$ mm·a^{-1} for the nearby swampy area, where the peat was excavated. Presumably, the small groundwater recharge is caused by a large actual evapotranspiration by phreatophytes. The groundwater tritium levels were lower than the average annual rainfall levels, possibly because evapotranspiration fully removed the summer precipitation with its higher tritium levels.

Hydrological considerations based on sedimentological analysis of the soil at the Best location and evaluation of the groundwater composition supported the value determined for downward flow, as estimated from groundwater tritium levels. A vertical component of flow was calculated at roughly $I=110$ mm·a^{-1}. A large part of the average rainfall excess, which is in the order of 250 mm·a^{-1}, will be discharged by surficial flows at the parcel. Extrapolation of the Best data is not easy, but it is plausible that in all the cases where less pervious layers of great areal extent are present at shallow depth, the hydrological situation may similarly lead to a considerable surficial discharge of rainfall. Groundwater travel times in the saturated zone will then be relatively large.

Meteorological approach

The potential annual evapotranspiration of agricultural crops E_p was approximated by applying the Penman open water evaporation, E_o, or the related reference evapotranspiration E_r, multiplied by so-called crop factors. The long-range average precipitation and evaporation over many years are available. An elaboration for the Venhorst detailed investigation resulted in values of $P=740$ mm·a^{-1} and $E_p=500$ mm·a^{-1}, with $P-E_p=240$ mm·a^{-1}. The tritium data indicated a groundwater recharge of 290 mm·a^{-1}. The difference is caused by the actual evapotranspiration, E_a, being smaller than the potential value. The calculated difference of $E_p-E_a=50$ mm·a^{-1} roughly corresponds to the value of the expected reduction in evapotranspiration (Werkgroep HELP, 1987).

The results of the investigations on ten grassland farms dispersed over the Netherlands indicated values for the actual evapotranspiration, which were 10 to 90 mm.a^{-1} smaller than the potential evapotranspiration. The median value of 60 mm·a^{-1} again corresponds to the HELP prediction.

The same conclusion follows from an evaluation of the observed tritium levels in wells of the monitoring networks. If surface runoff is taken to be neglected for monitoring wells in areas with a fully sandy soil, the combined effect of a reduction in evapotranspiration and the application of sprinkling water leads to an average increase in groundwater recharge in the order of magnitude of 70 mm·a^{-1} for agricultural areas. The increase is in agreement with the expected reduction in evapotranspiration for cases where crops are cultivated in soils with groundwater levels corresponding to GT VI. Moreover, calculated values for groundwater recharge, based on tritium levels, correspond to values estimated from regional water balances. Hence, for agricultural areas, the values of groundwater recharge based on an interpretation of groundwater tritium levels are in good agreement with values of the rainfall excess. These are estimated from meteorological data and take into account soil and groundwater features, including water shortages in an average summer period. Thus, the estimates of rainfall excess, derived from meteorological data in combination with the local soil and groundwater features, constitute a good basis for estimating the groundwater recharge in agricultural areas.

The groundwater recharge in areas with a natural vegetation was considered in more detail for the Veluwe region. The different values determined for the evapotranspiration of heathlands showed less agreement. In all likelihood, this was due to the character of the areas, dominated by heathlands, varying widely. Areas with an almost bare soil are present, but so are those covered with tall grasses. Because open spaces and areas with trees behave differently, the interpretation of tritium data from forest areas had to take into account problems of scale. The estimates of the overall groundwater recharge, derived from the average tritium levels of 'sprengen' water, agree with the results based on condensation studies. Parts of the recharge areas do not have a forest vegetation and, hence, the average evapotranspiration will be less. The same situation, where a larger part of open space is in the recharge areas, will also prevail with regard to monitoring wells, again causing a decrease in evapotranspiration if compared to a full forest. It can be concluded therefore that:

- The actual evapotranspiration of areas in the Veluwe region with a dense forest vegetation approximates the Penman open water evaporation (E_o).
- The evapotranspiration of inhomogeneous forests, including forest lanes and open spaces, will be less than the Penman open water evaporation. The average evapotranspiration for the Veluwe forested areas is roughly $E_a=0.9*E_o$.

The groundwater recharge, estimated from the tritium levels in samples from monitoring wells in forest areas of the other sandy districts, assumes larger values than for the corresponding Veluwe situation. Possibly the most important reason is the location of the monitoring wells, such that groundwater recharge in open spaces also influences the observed levels. The Veluwe results are extrapolated to the other forest areas.

The average actual evapotranspiration in non-forested dune areas with a natural vegetation is of the order of E_a=500 mm·a^{-1}, roughly implying that E_a/E_o=0.7. The range of values is large for dune areas, probably due to a variable vegetation and/or the hydrological situation at the observation wells. The groundwater in the dunes is influenced by the effect of some open water evaporation from excess rainfall moving along the dune slopes, which leads to a modest (about 0 to 20%) enrichment in tritium levels.

Adaptation of the tritium time series for rainfall

Measured groundwater tritium data and the extrapolated time series of rainfall levels were generally consistent for the whole period, which supports the synthesized tritium series in rainfall. Only for the years 1962-1966 did a systematic deviation become apparent for rainfall tritium levels. Observed tritium levels in groundwater, recharged in that period, were systematically lower than would be expected on the basis of rainfall levels in those years. The large tritium levels, observed in Vienna rainfall during the years 1962-1966, cannot fully be traced back to the groundwater of the Netherlands. The comparison of the estimated tritium levels in rainfall and the tritium levels observed in groundwater have led to a 50% reduction in the series of tritium levels in rainfall for the years 1962 to 1966, as obtained by an extrapolation of levels measured in the Vienna precipitation. There is evidence that also the regional factors in the years before 1970 will deviate from values determined for the period after 1970, but data are lacking for a more detailed evaluation. The regional factors, derived for the period after 1970, are assumed to apply for the earlier period as well. Hence, for groundwater studies, a reference series of tritium levels in rainfall is available, allowing estimates of the rainfall levels anywhere in the Netherlands at any time in the past.

Annual averages of rainfall levels were matched with groundwater tritium levels. Due to effects of open water evaporation (enrichment) or to the occurrence of surficial discharge (seasonal effects), deviations may occur in areas with a natural vegetation. For the interpretation of tritium levels in the groundwater of forest areas, the local rainfall levels have to be multiplied by a factor of roughly f=1.5 before the values of rainfall and groundwater levels correspond.

Regionalization

A great majority of observed tritium levels indicated one coherent groundwater flow pattern - the one occupying the Pleistocene aquifer - except in the areas where the subsurface contains a relatively thick series of poorly permeable clay layers. Other observations, for instance, in the Veluwe 'sprengen', support this conclusion. The tritium data, available for large parts of the sandy regions in the Netherlands, does not confirm the assumption of superimposed (nested) groundwater flow systems. The development of a system analysis to distinguish separate groundwater flow systems will be of limited use for the sandy areas.

In some areas, the occurrence of surficial discharge will reduce the amount of water available for groundwater recharge. Initial estimates are given for areas with shallow groundwater tables. For areas where the shallow sandy soil contains clay layers, hampering the downward percolation of water, an interpretation of groundwater tritium levels results in a possible surficial discharge of roughly 50% of the annual rainfall excess. In estimating groundwater recharge from rainfall excess, the amounts of locally discharged water cannot be neglected; however, the effects can hardly be generalized.

The areal distribution of groundwater recharge has been elaborated for the sandy regions of the Netherlands with the help of a Geographical Information System and taking into account the interpretation of the local and regional surveys. The resulting values, valid for grids of 25 ha, were used to calculate groundwater travel times based on the equation:

$$t=(p*D/I)*\ln[D/(D-z)]$$

Values for the groundwater recharge, I, following from the GIS elaboration and values for the aquifer thickness, D, were estimated from general hydrogeological information; the porosity p=0.35. The results were presented in the form of three maps, showing the groundwater travel times at: z=5 m; z=10 m and z=25 m, respectively, where z is the depth below the phreatic groundwater table. The screen depths of the various monitoring networks were used for z.

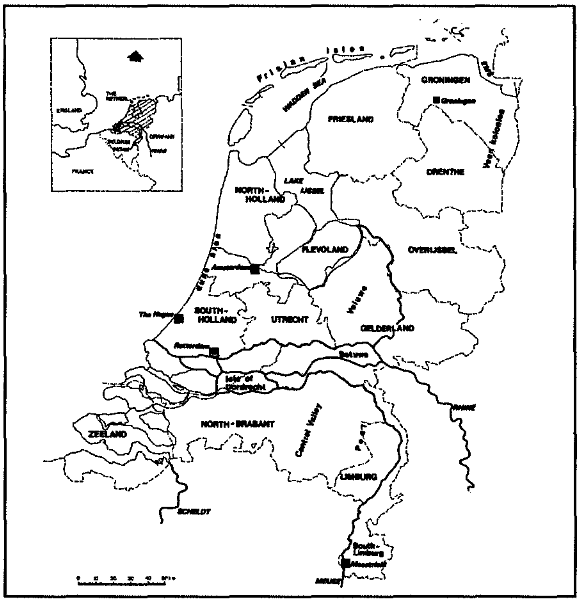
1. INTRODUCTION TO THE HYDROLOGY OF THE NETHERLANDS IN RELATION TO ENVIRONMENTAL SOILPROBLEMS

1.1 Environmental hydrology in relation to soil quality

Hydrological research in the Netherlands (*Fig.1.1*) has been extended in recent years to include problems related to environmental issues. Near industrial sites, the soil may receive chemical wastes which are dangerous to human life or threatening the ecological balance. Many rural areas suffer from high loads of fertilizer and excess manure, implying a percolation of residues. The aerial deposition of pollutants in nature reserves has increased. A resulting diffuse pollution endangers, not only the economic use of the soil, like the abstraction of groundwater, but also its ecological quality (Langeweg, 1989). Although the effects of diffuse pollution at a specific location may be smaller than the effects of point sources, the threats to the environment are larger because of the diffuse pollution's widespread occurrence.

Results of hydrological investigations can lead to a better understanding of environmental changes due to soil contamination, not only with regard to open water, but certainly also concerning the soil. From an environmental viewpoint, it is useful to consider soil as the solid part of the subsurface, being inseparably combined with the fluids (water), gases and biota

Figure 1. Situation and regional division of The Netherlands



within the solid matrix. Diffuse contaminations, as well as many point sources of pollution, attack almost exclusively at land surface. Water forms the transport mechanism, bringing the pollution to deeper soil layers, and/or to the draining surface water and ultimately to the sea. Many processes influence the fate of a particular pollutant during transport, depending on the character of the soil layers encountered, and on the water flux and its pathway. Hence, groundwater flow is a crucial factor for the behaviour of pollutants within the soil. Hydrological investigations can reveal flow lines and travel times of groundwater. The transport route of a pollutant and the changes in its occurrence can be estimated on the basis of the direction and velocity of groundwater flow.

Not every region runs the same risk with regard to diffuse pollution. The identification of the most threatened areas follows from a general overview of the country. A review of the hydrological situation of the Netherlands presented in the following pages will reveal that sandy areas are the most vulnerable to diffuse pollution. The present study aims at an evaluation of shallow groundwater flow in the sandy regions.

The investigations focus on soil quality as an environmental factor. The hydrological methods used for evaluating the effects of diffuse pollution, caused by the application of fertilizer and excess manure in the rural areas of the Netherlands, can be characterized as belonging to environmental hydrology. Although environmental changes may be linked to all human interferences in the hydrological cycle (*Fig.1.2*), it is especially the shallow flow of groundwater that is important in environmental hydrology. The reason is that many factors determining the environmental situation are related to processes near the land surface. The aspects considered include:

- an estimation of the amount of groundwater recharge;
- a determination of downward groundwater flow and travel times;
- a reconnaissance of structure and composition of the shallow soil.

The groundwater in sandy areas is recharged by the rainfall excess, which is the difference between precipitation and actual evapotranspiration. These two factors can be estimated on the basis of normally observed meteorological parameters. Groundwater re-

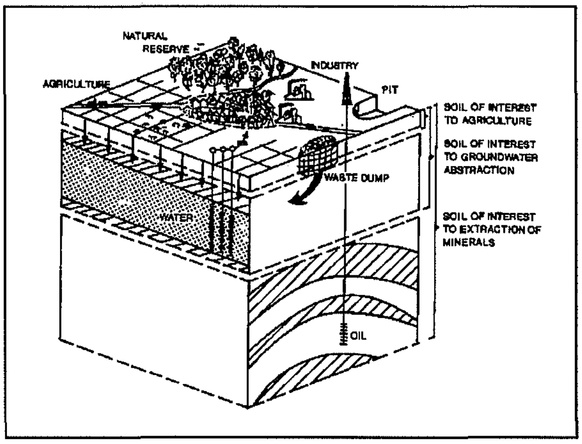


Figure 1.2. Economical activities with a possible environmental impact on soil quality

charge initiates a downward movement of water in the unsaturated zone and, subsequently, a vertical flow in the saturated layers of the subsurface. Following from hydrological considerations, the vertical flow to the saturated zone can generally be approached by a downward relatively constant flow, both in volume and composition. This flow results in horizons of a constant groundwater age.

The most direct way to investigate the soil is to collect soil samples from drillings. Sedimentological methods were used in the local investigations to present a detailed analysis of the soil structure and composition. Rougher, but less laborious reconnaissances of the shallow layers of subsurface, including the groundwater composition, are formed by geo-electrical and electro-magnetical surveys. Variations in groundwater composition were used to assess the hydrological situation, especially the groundwater flow patterns.

If compared to the fluctuations of tritium levels in rainfall over time, groundwater travel times can be determined by the vertical variation of the groundwater tritium levels. A reference series of the tritium amounts in rainfall in the Netherlands has been compiled for groundwater studies. The interpretation of groundwater ages followed from a combination of the tritium analysis with an initial estimate of groundwater flow conditions, as assesssed by hydraulic methods.

The hierarchy of investigations consisted of carrying out detailed studies at specific locations, using the results to compose regional overviews of the four major sand districts and the coastal dunes of the Netherlands. Five detailed studies were elaborated to further develop the methodology. The regional overviews were based on local investigations at ten farms, dispersed over the sandy areas and on a large number of monitoring wells, where two or three tritium observations were available for each well. Investigations of the Veluwe nature reserves to estimate groundwater recharge were largely based on a hydrological interpretation of the composition of groundwater and stream water (the "sprengen"). The regional results were subsequently generalized for the national scale.

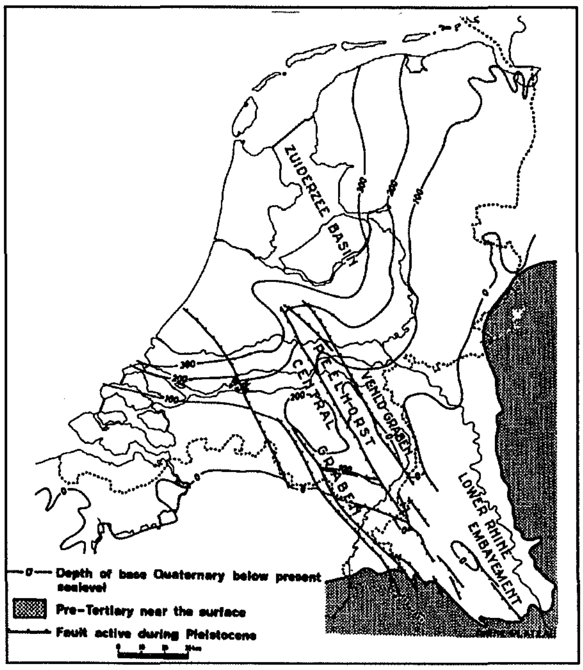
Groundwater recharge determinations, based on groundwater tritium data collected from observation wells, could be extrapolated with the help of generally available soil and meteorological data. Finally, the recharge determined was used to calculate groundwater ages. That it is possible to assess an areal distribution of groundwater recharge and travel times over all the sandy regions in the Netherlands can be concluded from these investigations.

1.2 Major hydrological features of the Netherlands

1.2.1 Hydrogeological structure

The groundwater hydrology of the Netherlands is controlled by the presence and the lithology of unconsolidated Quaternary sediments (RGD, 1975), deposited in a subsiding basin. The axis of the basin dips to the northwest (*Fig.1.3*), resulting in the largest thicknesses of the Quaternary formations in the

Figure 1.3. Depth of the Quaternary sediments (Zagwijn, 1989)



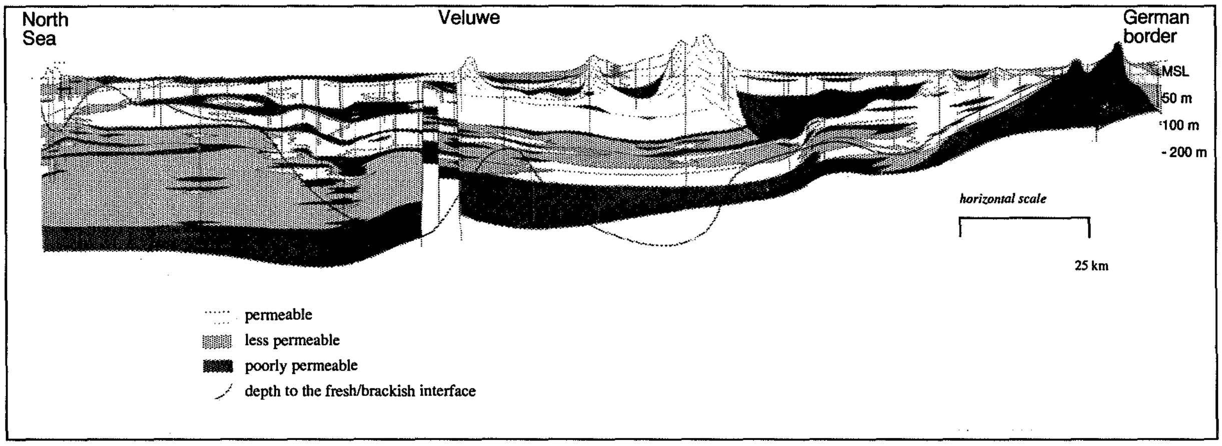
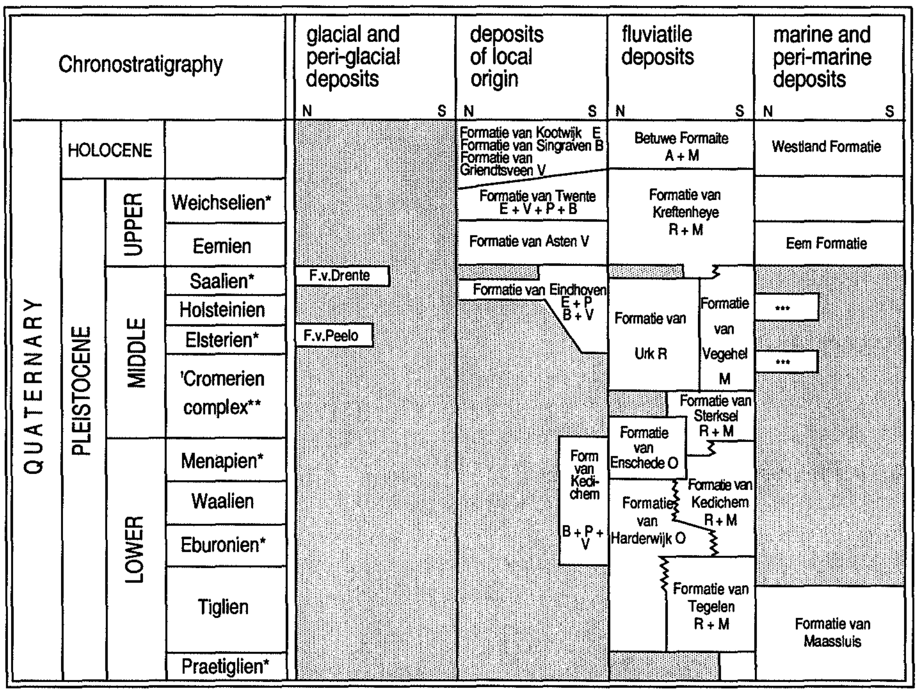


Figure 1.4. West to east hydrogeological cross-section of the center of The Netherlands acc. to Jelgersma (1977)

northwestern part of the country (Zagwijn, 1989). At the eastern border, Tertiary and even older sediments crop out. Where Quaternary sediments thin out, Upper Tertiary layers may form exploitable aquifers. Also the deeper strata of the subsurface contain groundwater. However, the permeability of deeper layers is normally low and the groundwater is brackish. The South Limburg region occupies a special position, insofar that aquifers, consisting of Cretaceous limestone, covered by aeolian loesses of a Pleistocene age, are exploited

The Pleistocene age consisted of a succession of cold and warm periods. The climatic conditions, along with important sea-level changes and tectonic movement, gave rise to an alternation of coarse and fine sediments. Very thick aquifer systems are present in the northwest part of the country. Aquifers are less important at the margins of the basin. Near the eastern border there are no exploitable aquifers at all in some areas. The Upper Tertiary aquifers along the southern border only reach a shallow depth. During interglacial periods, finer sediments were deposited, subdividing the aquifer system over large areas. In the last cold period, the Weichselian stage, large parts of the country were covered by aeolian cover sands and loesses, which may now act as semi-confining layers. Also the boulder clay, deposited underneath the ice sheets of glacial periods, forms a semi-confining layer. An overview of the hydrogeological structure of the Pleistocene formations is presented in *Fig.1.4*, with the terminology indicated in *Fig.1.5*.

Figure 1.5. Terminology of Pleistocene formations (RGD, 1975)



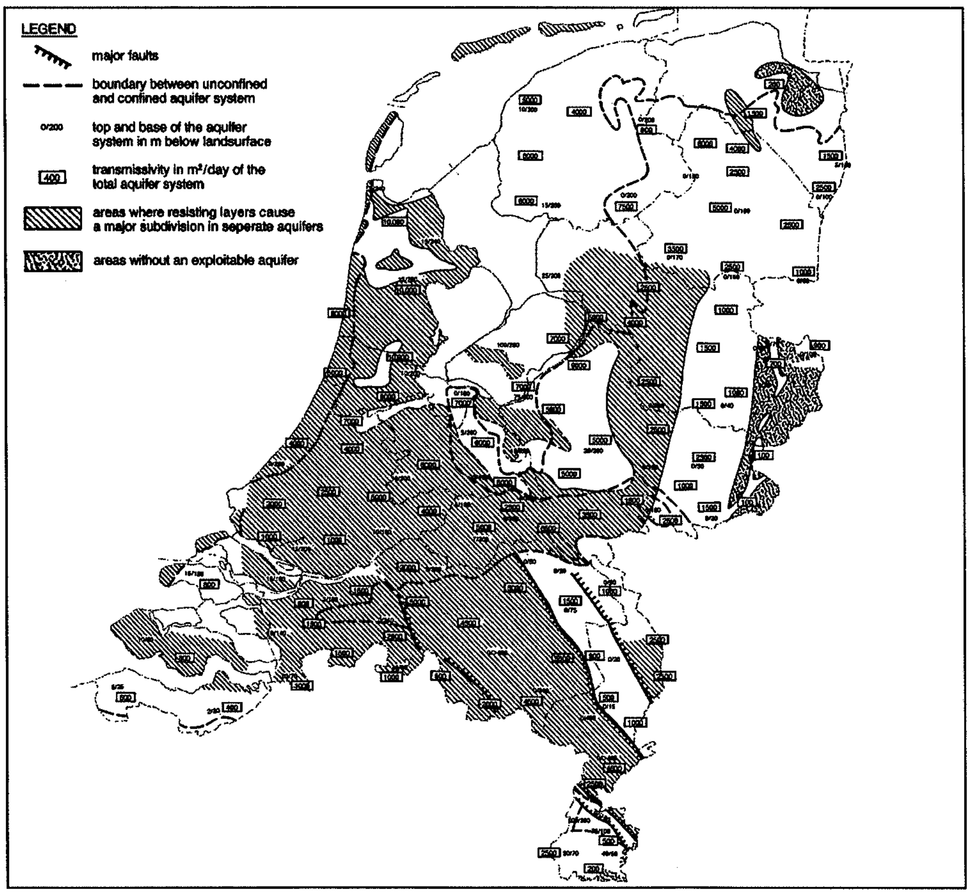
Tectonic activity influenced especially the hydrogeological situation of the southern part of the country. Fault zones affected the subsurface, and the presence and magnitude of aquifers and confining layers. After the Middle Pleistocene period, the rising Peel Horst hindered a further deposition by the major rivers in west North Brabant. There, shallow layers are largely of a Lower and Middle Pleistocene age, often covered with relatively thin layers of younger deposits of a local origin.

The Holocene sediments consist predominantly of clay and peat layers, deposited in a lagoonal and deltaic environment due to the post-glacial sea level rise. They are present in a broad coastal zone and reach a thickness of more than 20 m near the coast (*Fig.1.4*). At the coast, a dune ridge has originated, constituting an aquifer system containing a fresh groundwater lens, the shape of which is determined by the width of the dune zone and the groundwater recharge. Land inward, the Holocene layers thin out; they are almost lacking in the eastern and southern parts of the country.

The whole subsurface, consisting of Quaternary sediments, acts as one, interconnected, aquifer system. The top and the bottom of the aquifer system as well as its total transmissivity are represented in *Fig.1.6.* Values of transmissivity resulted from the interpretation of a large number of pumping tests executed by various research institutes in all parts of the country. In the province of North Holland, a transmissivity of more than 10 000 m^2 per day was determined at the deepest part of the Quaternary basin (*Fig.1.6*). Transmissivities are lower at the margins of the basin. Near the eastern border, values are in the order of some hundreds of m^2 per day. The shallow aquifers along the southern border have transmissivities in the order of 1000 m^2 per day.

In general, the upper sub-aquifer in the sandy regions will be an unconfined aquifer, having a phreatic groundwater table. However, when considering local situations, it may turn out that brook loams or other less permeable layers (not necessarily represented in *Fig.1.6*) will cover the upper aquifer, thereby forming semi-confining layers. Over large areas (*Fig.1.6*), intercalated clay layers within the Pleistocene sand layers may constitute semi-confining layers, dividing the system in two or more sub-aquifers. These clay layers can exert a considerable hydraulic resistance, but will never be fully impermeable. Hence, the Pleistocene aquifer system, including its deepest

Figure 1.6.Top and base of the Quaternary aquifer system and values of transmissivity (UN, 1991)



parts, hosts a coherent groundwater flow, taking part in the active hydrological cycle.

In areas covered by Holocene deposits, the same Pleistocene aquifer system is present in the subsurface, but is confined by surficial clay and peat layers. The aquifer system receives a smaller, or even no, recharge from local precipitation, except for the sandy dunes. The groundwater recharge in the coastal regions consists of a lateral inflow of groundwater recharged in higher areas, often in combination with a small local recharge. The fresh groundwater underneath the coastal dunes rests on a body of brackish groundwater. The brackish groundwater is not fully stagnant; it will generally move land-inward, but mostly at a lower flow rate than the fresh groundwater above it.

The subsurface below the Quaternary sediments consists of older unconsolidated and often also semi-consolidated sediments. These sediments still contain groundwater, but, in general, the transmissivities and also the flow rates will be smaller by one or more orders of magnitude than those in the Quaternary aquifer system. Except for the Upper Tertiary layers in the southern part of the country, the older strata are not exploited for public water supply. In recent years, the hydrogeology of the deeper subsurface has been investigated to assess its potential for the disposal of hazardous waste (Glasbergen, 1990).

1.2.2 Climate and the average national water balance

The climate of the Netherlands is moderate and essentially oceanic. Average monthly temperatures at De Bilt, the main weather station in the centre of the country, vary from 2 °C in January to 16 °C in July. Precipitation in the Netherlands largely occurs in the form of rainfall, with a relatively regular distribution over the year (*Fig.1.7*). The annual amounts of rainfall vary from year to year, generally between 500 and 1200 mm·a^{-1}; the average is 775 mm·a^{-1}. Wet and dry years occur more or less in a regular series. The 1960s were relatively wet years, the 1970s relatively dry and 1980s relatively wet again. A full comparison is hampered by the fact that the technique of rain gauging has been improved in recent years. The present rain gauges are of the ground type, implying slightly higher values for measured rainfall than with those formerly used, which were more elevated. Moreover, regional variation is present.

The actual evapotranspiration of a given area depends on the meteorological circumstances, local vegetation,

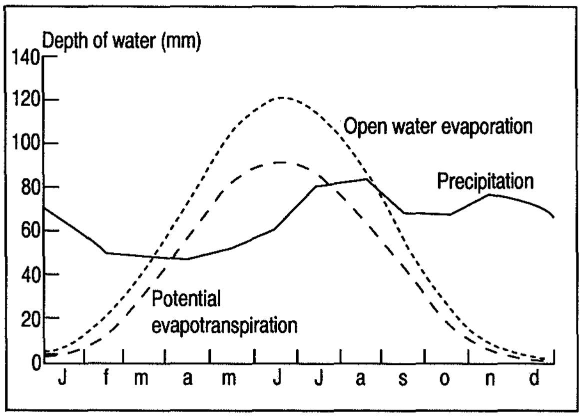


Figure 1.7. Mean monthly precipitation, open water evaporation and potential evapotranspiration (TNO, 1986).

and soil and groundwater features. It is hardly possible to measure the actual evapotranspiration directly. A much used approach is to determine the open water evaporation according to Penman (1948) and to derive from that value the potential evapotranspiration valid for grassland (*Fig.1.7*). The actual evapotranspiration can be estimated by taking into account the type of vegetation in combination with the availability of water in the soil; the actual evapotranspiration will be equal to or less than the potential evapotranspiration. Although the variation in the mean annual evapotranspiration depth is small, levels of evapotranspiration may vary considerably over the months (CHO-TNO, 1988), as shown in *Fig.1.7*. In an average year, a water surplus in the winter months and a deficit in the summer months occur.

A water balance of all water passing through the country in an average year is given in *Table 1.1* (TNO, 1986). By far, the largest terms in the balance are the inflow and outflow of the River Rhine. In former times, the River Rhine water only passed through the country, causing a nuisance mainly during high level periods. At present, the water is used for different purposes at an ever-increasing rate. Projects to bring Rhine water to regions suffering from water deficits have been realized.

The maximum amount of water which can infiltrate under natural conditions into the saturated zone is equal to the amount of precipitation minus the actual evapotranspiration (called the rainfall excess). The average annual rainfall excess in the Netherlands is 275 mm·a^{-1} (*see Table 1.1*). In specific situations, a surficial discharge reduces the groundwater recharge in deeper layers. For a determination of the downward groundwater flow in the saturated soil, yearly variations in groundwater recharge are less important than a long-term average. In local investigations, the regional variation is important.

Table 1.1 The water balance in water volume and depth for an average year in the Netherlands (UN, 1991)

IN	10^6 x $m^3 \cdot a^{-1}$	$mm \cdot a^{-1}$	OUT	10^6 x $m^3 \cdot a^{-1}$	$mm \cdot a^{-1}$
rainfall	30 100	775	evapotransp.	19 500	500
Rhine infl.	69 000	1775	water use	5 000	130
Meuse infl.	8 400	215	river outflow	86 000	2210
small riv.	3 000	75	groundw. outflow	50	1
TOTAL	110 500	2840	TOTAL	110 550	2840

1.2.3. Landscape, soil and hydrography

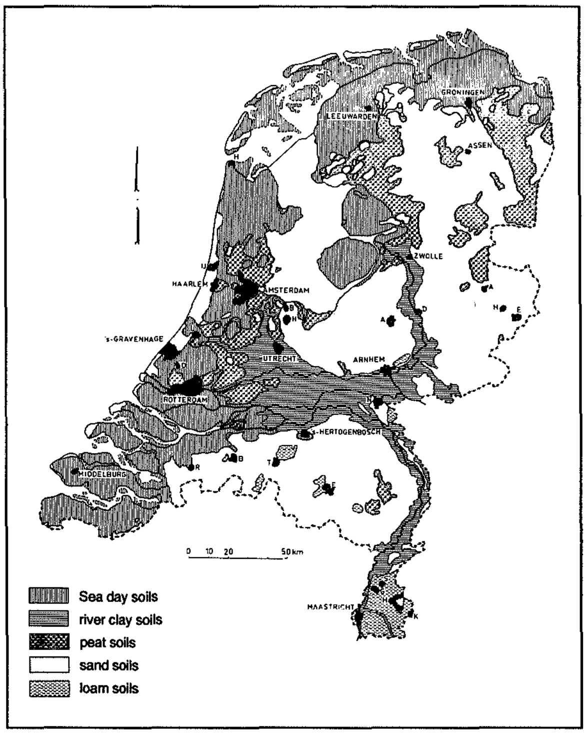
The sedimentation during the Pleistocene age resulted in a vast and predominantly flat fluvial plain, gently dipping to the northwest. Depending on the transport capacity of the subsurface, a stream pattern developed, draining the groundwater (De Vries,1974). The presence of ice sheets during glacial periods had a strong influence on the morphology. Deep valleys were scoured, either by melt water, or by the ice itself. Many of the valleys can still be recognized in the present stream patterns of the northern and eastern regions. The sandy material removed by the ice was pushed into ridges; the low hills resulting are at present important recharge areas. Because of deep groundwater levels, the hills are less suited to agriculture. They have mostly been planted with forest, and are now nature reserves and important recreational areas. The glacial valleys were subsequently filled in, mainly with poorly permeable sediments. They still are relatively low and wet areas. In many places, peat layers developed in such moist areas. Tectonic activity influenced the landscape of the southern part of the country. Fault zones affected the stream patterns. The recent genesis of the relatively high Peel area was not matched by the development of an adequate stream system and peat bogs originated near the water divide.

The Holocene age was characterized by a relatively high rise in sea level (Jelgersma, 1979), which led to the deposition of marine sediments in a broad coastal zone. However, large peat bogs also originated because of rising groundwater levels. Three major zones exist (*Fig.1.8*) in the Netherlands:

- The elevated sandy areas, geomorphologically formed during the Pleistocene age;
- the relatively high areas of the most recent coastal accretions, predominantly covered by clayey soils;
- a relatively low transition zone with peaty soils.

As early as the Middle Ages, the inhabitants of the coastal regions improved the drainage of the clay and peat regions by digging ditches and canals. At present, almost the full drainage system in the lowlands of the Netherlands is artificial and based on a forced discharge of excess water by pumping. Most of the surficial peat layers were excavated to supply fuel. Large lakes were created by this peat mining, many of them subsequently reclaimed and made into polders. The former raised bogs in the higher regions were directly turned into agricultural lands, drained by a system of ditches and canals. The soil consists mainly of sand but still contains a large organic component. The sandy regions were used for an extensive agriculture, leading to a gradual degradation of soils, such that vast heathlands, and even bare soils with shifting sands, developed. The situation changed af-

Figure 1.8. Major soil types in The Netherlands according to Stiboka (1960)



ter the introduction of fertilizer, about 100 years ago. Heathlands were turned into pastures and only the most infertile soils were planted with trees. Land reclamation in the sandy regions continued up to the middle of the 20th century, including an extension and a deepening of the natural stream systems to dewater low soils. The development still continues in the form of tile drainage installation.

1.2.4 Groundwater heads and flow directions

The recharge of groundwater in the Netherlands is complicated because it depends on the local topographical situation. In the west Netherlands polder areas, recharge by surface water, infiltrating at nearby river beds or from other surface water, is the major source of groundwater. Infiltration of rainfall used to be the only form of recharge in the sandy areas. Important recharge areas are the ice-pushed hills, the Drenthe Plateau and the Peel region. Part of the rainfall excess was discharged by surficial components, leaving a smaller amount of water for the actual groundwater recharge. In the present situation, groundwater recharge is sometimes increased by sprinkling from surface water or from groundwater. Moreover, an abstraction by wells may lead to a decrease of surficial discharge and, hence, an increase in groundwater recharge. Parts of the coastal dunes became important sites for artificial recharge by surface water transported to the dunes and infiltrating from ponds.

The groundwater, originating in areas of natural or artificial recharge, will flow to areas where the groundwater is again discharged into draining open water, or by evapotranspiration. The vertical flow in aquifers may usually be neglected in comparisons with horizontal flow components. Thus, the flow pattern can be shown by isohypses, representing lines of equal groundwater heads. Regional isohypses valid for the Netherlands, show the large-scale directions of the horizontal groundwater flows (*see Fig.1.9*). Discharge areas can take the form of a river zone, with relatively shallow groundwater levels, where at least the shallow groundwater will have an upward velocity and seep into open water courses. The deeper groundwater may continue to flow in the direction of a more distant draining water course. In the Netherlands situation, also some of the polder areas have a strong upward seepage, discharging the incoming groundwater flows, which sometimes have originated in sandy areas far away from the polder. Prominent examples of polders receiving large

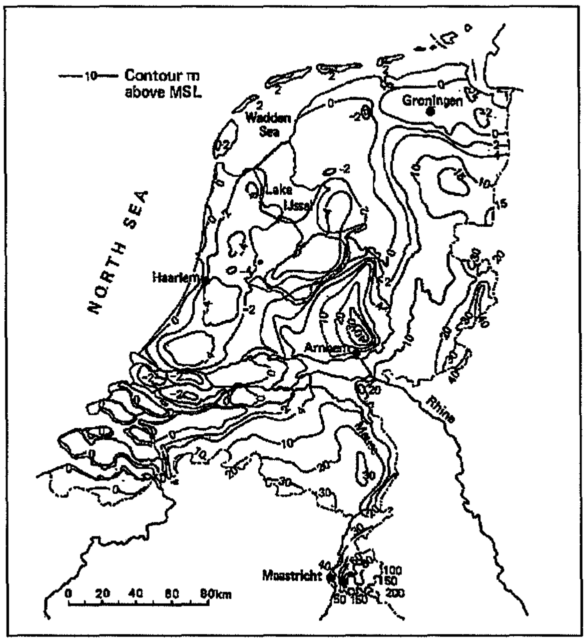


Figure 1.9. General groundwater isohypses in the Quaternary aquifer system (UN, 1991)

amounts of seepage water are those in *Fig.1.9,* where the groundwater levels are below m.s.l.-4 m. The deep polders are the focal points of regional groundwater flows.

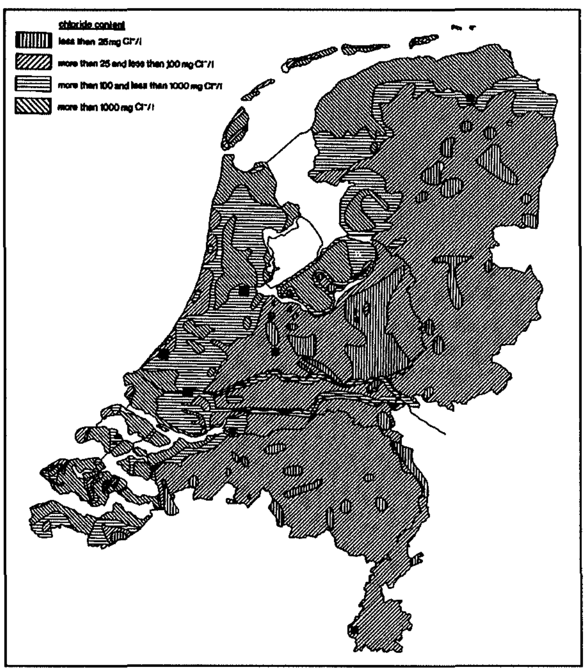
Certainly evident is that on a local scale the situation will be more complicated than suggested by *Fig.1.9,* due to the influence of small-scale topography on shallow groundwater systems. Aquifers are not homogeneous; they always consist of pervious and less pervious layers, having an impact on the local flow situation. The discharge of rainfall excess in a region can follow different, but interfering pathways. In many discharge areas, a complicated situation occurs: in the upper layers a downward flow may prevail but the deeper groundwater will already flow upward, where it will be discharged by the local open water. The base of the downward flow depends on the local hydrological situation.

1.2.5 Groundwater composition

The salt brought in by the various floodings of the sea during the Holocene age can still be traced back to the shallow soil. Chloride concentrations in the upper groundwater of shallow aquifers are represented in *Fig.1.10.* which was composed on the basis of regional studies, including the results of geophysical measurements. Good agreement exists between the area with increased chloride contents and the maximum reach of the marine transgressions; the area covered by Holocene marine deposits is only slightly larger. The chloride concentrations are relatively low if compared to the chloride levels of sea water (Volker, 1961). The salt content in the shallow subsurface was redistributed by the creation of high and low polders in the coastal region, resulting in an intensification of the groundwater flow and changes in flow patterns (Meinardi, 1991). Shallow groundwater in the clay and peat regions is often brackish, but shallow groundwater in the sandy regions of the Netherlands will generally be fresh.

In almost the whole country, the groundwater at greater depths is brackish or saline. The interface between fresh and brackish groundwater is at a variable depth. The origin of the salt in the deeper groundwater has to be sought mainly in older marine sediments of a Lower Pleistocene and Tertiary age. The chloride concentrations are gradually increasing with depth. The salt distribution in the lower layers of the Quaternary sediments has largely resulted from lateral dispersion of salt in the aquifer system, derived from a marine base and caused by a horizontal groundwater flow (Meinardi,1991). In some cases, the withdrawal of originally fresh groundwater has caused the attraction of deeper saline water, notably at places where the natural situation had already caused the occurrence of brackish groundwater at relatively shallow depths (e.g. salt water wedges at groundwater divides).

Figure 1.10. Chloride concentration in mg/l at the top of the aquifer system



In sandy areas, largely recharged by precipitation, three factors play a predominant role with regard to the major groundwater composition:

- The ratio between precipitation and the amount of actual groundwater recharge determining the condensation of the constituents brought in by the rainfall.
- Anthropogenic pollution attacking at land surface or already contaminating the rainwater composition.
- Processes in the soil changing the groundwater composition (physical, biological and chemical changes).

Under natural circumstances where direct contamination at land surface is less important, the rainfall is the main source of dissolved compounds in groundwater. Elements of the rainwater composition can still be recognized in the groundwater composition of nature reserves. However, before rainfall contributes to groundwater recharge, part of the water will evaporate. Evaporation is a selective process. Pure water is removed and dissolved chemical compounds remain in the non-evaporated water, but in a condensed form. If strong differences in the actual evaporation have occurred, the groundwater composition will show a corresponding variation. On the other hand, if the groundwater composition of nature reserves is known, indications can be obtained about the condensation ratio and, hence, about the magnitude of the actual evapotranspiration.

Important point sources of pollution in the Netherlands are sanitary landfills and the dumping of waste materials at industrial sites. Although the effluent of point sources may be strongly polluted, the effect is mostly restricted to the nearby surroundings (UN, 1991). Diffuse sources of pollution are:

- Use of fertilizer and other chemicals in agriculture;
- Deposition of excess manure;
- Air and rain-water pollution coming from various sources.

In *Fig.1.10*, also areas outside the coastal regions have been mapped. Increased chloride concentrations in sandy regions indicate the effects of diffuse pollution. The constituents in polluted groundwater will change due to soil processes. In general, a diffuse pollution will lead to an increase in concentrations of dissolved compounds in groundwater. The differences between groundwater polluted by only atmospheric deposition and groundwater polluted by excess manure is indicated in *Figs.1.11* and *1.12*. Another remarkable feature is shown by the Venhorst observation well (*Fig.1.12*), where, at a depth of roughly 8 m, a transition occurs between the upper, heavily pol-

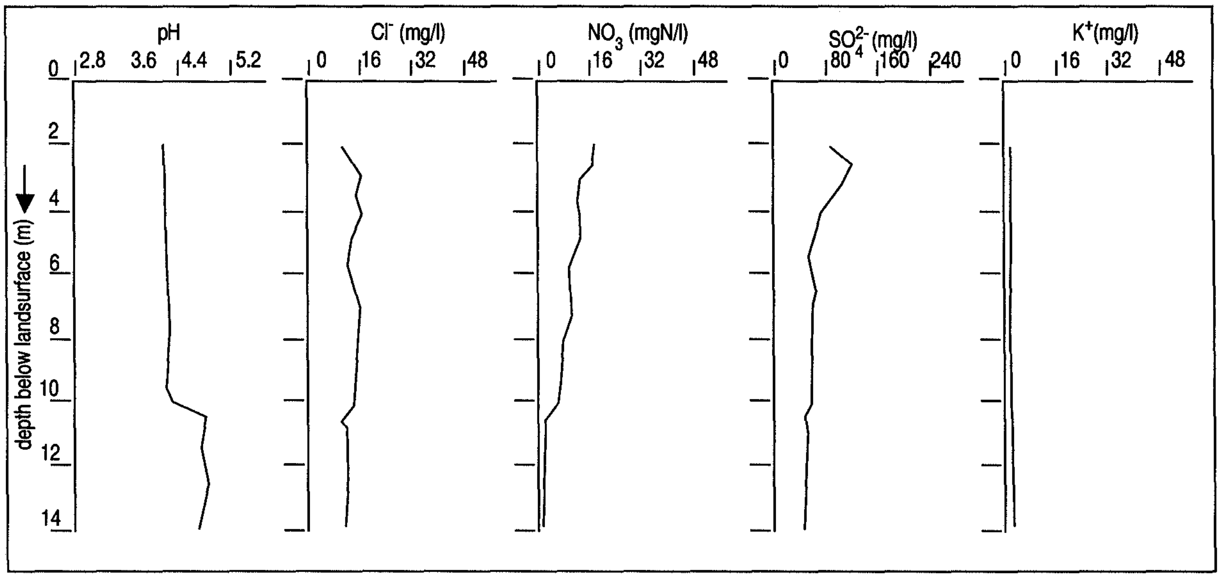
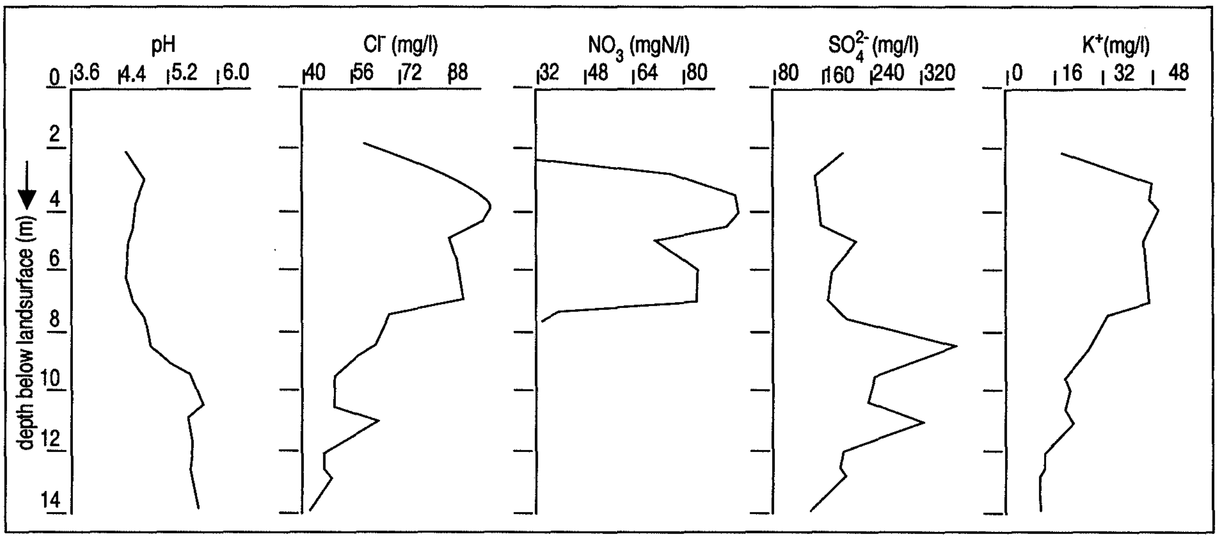


Figure 1.11. Vertical profiles of pollutants, derived from aerosols, in groundwater of a nature reserve in the Peel area (Rips forest)

luted, groundwater and the lower, less polluted groundwater. The difference is caused by groundwater recharge from a manure reservoir (point source) for the upper zone and a groundwater recharge from agricultural lands (diffuse source) for the lower zone. Hence, in a detailed investigation of the fresh groundwater composition, various groundwater types may be distinguished, each with its specific origin. Groundwater contamination, most often originating at land surface, is further transported in the subsurface by the movement of groundwater. Once the origin of specific groundwater pollution is known, the transport of dissolved compounds by groundwater flow can be estimated if the flow features are known. As well, the rate of groundwater flow components may be indicated by the distribution of a specific groundwater type in the soil if the origin of the groundwater composition (location and starting time) is known.

Differences caused by soil processes have a variable effect on the groundwater composition, which cannot always be exactly determined because of a lack of data concerning the many interfering factors. The possible effect of soil processes has to be taken into account when considering groundwater composition with the aim of describing hydrological processes. In general, the effects of soil processes are stronger at a passage of clay and peat layers, than during flow in sand layers. Notably, due to the occurrence of ad-

Figure 1.12. Vertical pollutants in the groundwater at a site of excess manure dumping in the Peel area (Venhorst)



sorption and biochemical processes, the concentrations of much anthropogenic pollution is reduced after the groundwater has percolated through clay layers.

1.3 Scope of the investigations

The main elements of groundwater recharge in the sandy regions of the Netherlands (*Fig.1.13*) are precipitation and evapotranspiration. In general, the downward vertical velocity of groundwater flow, initiated by a rainfall excess in the order of 300 $mm \cdot a^{-1}$, will be approximately 1 $m \cdot a^{-1}$ (at a porosity $p=0.35$). The pollution at land surface by fertilizer and manure slurry is relatively large (RIVM, 1991) in the sandy regions. A reduction of groundwater contents by soil processes hardly occurs. Hence, the dispersion of chemical compounds derived from diffuse sources is widespread in the aquifer systems of the sandy regions in the Netherlands (Boumans et al., 1989; Wit, 1988; RIVM, 1991).

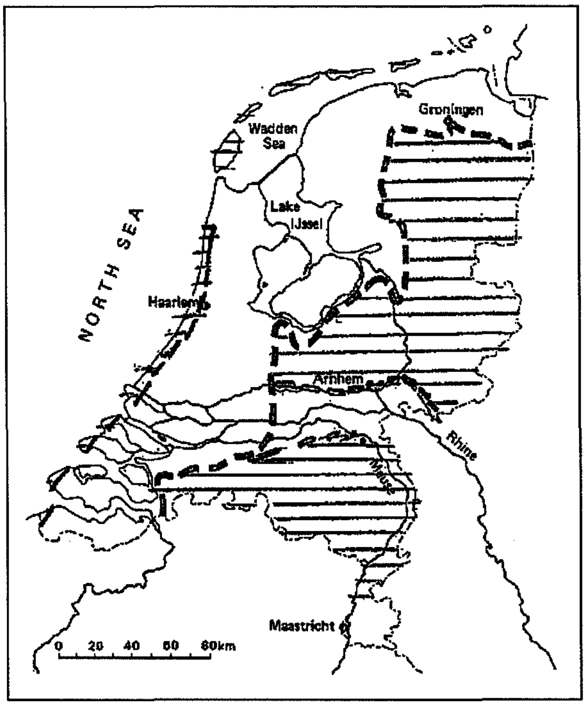


Figure 1.13. The investigated sandy regions

In the coastal regions, covered by clay and peat layers, the downward velocity is much smaller than in sandy aquifers and even absent for many areas. A contamination at the land surface will take much longer to arrive in the upper aquifer than it would take in sandy regions. Moreover, the percolation through surficial peat and clay layers may reduce the concentrations of contaminants because of adsorption and biochemical changes. Additionally, in many cases, the groundwater is brackish at the top of the sandy layers in the subsurface of the coastal regions, reducing the negative effects of groundwater pollution on economic activities and often also on ecological conditions.

Therefore, when investigating the hydrological situation with the aim of determining the effects of a diffuse pollution, the sandy regions are considered more important than the coastal zone, covered by clay and peat layers. Hence, the objective of the present study can be defined more precisely as such:

To assess the groundwater flow components, determining transport of diffuse contaminants, especially in shallow layers of the sandy regions.

Direct measurement of groundwater flow is hardly possible. The shallow downward percolation depends on groundwater recharge, which also cannot be determined directly. The recharge is initiated by the rainfall excess, which is related to topographical and meteorological features. However, the travel times of shallow groundwater can be calculated with the help of groundwater dating on the basis of its tritium levels. Travel times, vertical flow and groundwater recharge are twins in the sense that a knowledge of one parameter implies the possibility of estimating values for the others. The investigations were set up to assess the groundwater travel times at specific locations by interpreting the groundwater tritium levels. The results are extrapolated according to land use and meteorological factors, determining the values of groundwater recharge. The aim was to do a mapping of groundwater travel times in the sandy regions of the Netherlands. Both elements of study were investigated before but, to date,not combined. Herweijer (1985) and Meinardi (1983) used tritium data for age determinations. Van Drecht (RIVM, 1991) elaborated on meteorological data to determine the rainfall excess, recharging the groundwater.

2. GENERAL CONSIDERATIONS ON GROUNDWATER FLOW IN THE SANDY REGIONS

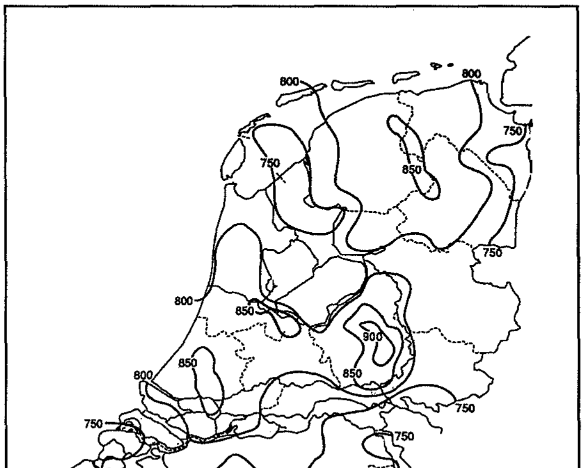
2.1 Discharge of rainfall excess; groundwater recharge

2.1.1 Precipitation

Precipitation in the Netherlands is measured by the Royal Netherlands Meteorological Institute (KNMI) at roughly 200 stations. The average annual precipitation over the period 1961-1990 is given in *Fig. 2.1*. For the comparison with groundwater observations, it is sometimes desirable to consider another period for the determination of long-term averages. The available long-term information, published by the KNMI, can be used to compose averages of varying series.

The effects of topography on amounts of rainfall become clear from *Fig. 2.1*. Due to a modest orographic effect, the hills of the Veluwe and of South Limburg receive increased amounts of annual rainfall. The local rainfall in these areas is more than 900 mm·a^{-1}. Contrary to this, the average annual rainfall in the western part of Zeeland is only 750 mm·a^{-1}. Also, along the eastern border of the country, from the east part of the province of Groningen to central

Fig.2.1 Average annual precipitation in mm·a^{-1} in the Netherlands in 1961-1990 (Source: Klimatologische Dienst, KMNI).



Limburg, the yearly rainfall is less than the average. Minimum amounts of average annual rainfall are observed in the eastern part of the province of North Brabant, whereas the province of Drenthe receives an average yearly amount of more than 800 mm·a^{-1}. The amounts of precipitation have a direct relation to the possible groundwater recharge.

The effects of artificial groundwater recharge in the past decades have to be taken into account. In large parts of the sandy regions of the Netherlands, sprinkling of agricultural lands has become a normal practice in dry years. The main purpose of sprinkling is to compensate incidental water shortages in summer periods, when the water needs of many crops exceed the precipitation. The water used is either local surface water, or groundwater, depending on the most easily available source. The effects of sprinkling on groundwater in the saturated zone had to be estimated because the amount of water used is unknown. Not all farmers have a sprinkling installation at their disposal and, also, the installations are not always rationally used. The amount of sprinkled water is in the order of 50 to 100 mm·a^{-1} (Van den Berg, 1982). The effect of sprinkling on the amounts of groundwater recharge is not the same everywhere.

Groundwater recharge is hardly ever equal to the amount of precipitation. A number of other discharge components reduces the amounts of water available for groundwater recharge, like the actual evapotranspiration and the surficial discharge by overland flow and interflow.

2.1.2 Actual evapotranspiration

Up to 1987, the KMNI determined monthly values for the open water evaporation E_o in 15 main meteorological stations using the Penman method. Since 1987, the KNMI has applied a method proposed by Makkink (1957) to determine values, E_r, for a reference evaporation. According to the KMNI (CHO-TNO, KNMI, 1987), E_r values are 0.8 times the E_o values. By taking $E_r = 0.8*E_o$, the values determined before 1987 may be compared to later values. Annual averages for the reference evaporation are given in *Fig. 2.2* for the period 1961-1990. The values are supposed to be equal to the potential evapotranspiration for grassland, being the dominant type of land

GENERAL CONSIDERATONS ON GROUNDWATER FLOW

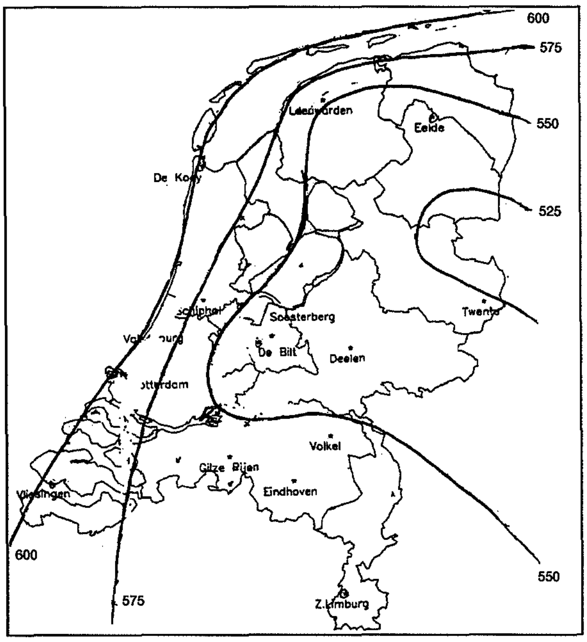


Fig. 2.2. Values representing annual reference evaporation E_r in mm·a^{-1} in the Netherlands over the period 1961-1990 (data: KNMI).

use. Values for other periods can be derived from KNMI data. Temperature and radiation are important contributing factors to the open water evaporation. The highest values of the annual averages of the open water evaporation were determined for the province of Zeeland in the south-west and the lowest value in the province of Drenthe in the north. The presence of the North Sea has a dampening effect on the variations in annual averages.

The potential evapotranspiration of various vegetations can be derived from the open water evaporation for an average situation by using so-called vegetation factors. Values for the open water evaporation, or the reference evaporation, have to be multiplied by factors in order to obtain the potential evapotranspiration for each type of vegetation. For a first estimate, the factors, originally proposed by Makkink (1960), based on the Penman E_0 can be used:

pine forest:	E_p=1.0*E_0;	**deciduous forest:**	E_p=0.8*E_0;
heathland:	E_p=0.9*E_0;	**grassland:**	E_p=0.8*E_0;
arable land:	E_p=0.7*E_0;	**"bare" soil:**	E_p=0.4*E_0;

Detailed vegetation factors for the potential evapotranspiration of agricultural crops are proposed by CHO-TNO, KNMI (1987). The above values for natural vegetation are less accurate. In recent years, a number of studies have dealt with different forms of evaporation in forest areas (Bouten, 1992; Dolman, 1987 and Tiktak and Bouten, 1994), indicating that the tree density is a major factor.

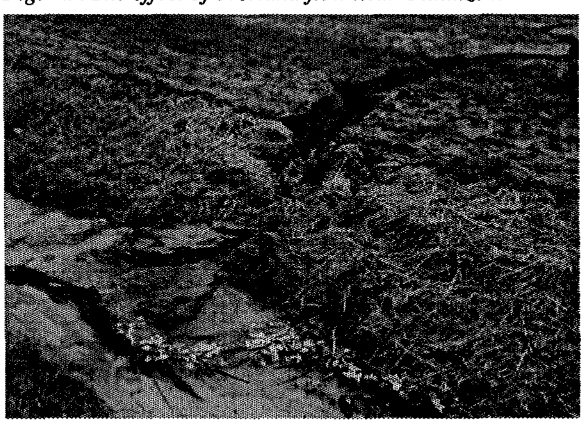
The actual evapotranspiration is often less than its potential value because of an insufficient water availability in the root zone to sustain the plant evapotranspiration. The reduction is a function of soil features, vegetation and groundwater depth. Average values in practical situations can be predicted by taking values for a reduction of the potential evapotranspiration in standard situations, as given in the so-called HELP tables (Werkgroep HELP, 1987). The tables indicate that the average reduction varies between 0 and approximately 100 mm·a^{-1} and, hence, is in the same order of magnitude as the amount of sprinkling water. Both factors have a similar effect of increasing the amount of groundwater recharge. Sprinkling results in a larger total precipitation, yet combined with a large actual evapotranspiration. Without sprinkling, the amount of precipitation is unchanged, but the actual evapotranspiration is smaller, resulting in roughly the same rainfall excess.

2.1.3 Surficial discharge of rainfall excess

Undoubtedly, a discharge of rainfall by overland flow and interflow will occur in the Netherlands situation: in regions with clayey and peaty soils, the presence of furrows indicates the need to surficially discharge excess water. Erosion gullies show the effect of overland flow (*Fig. 2.3*). Bon (1968) made it plausible that, at least in stream zones of sandy regions, a considerable amount of water may be surficially discharged (*Fig. 2.4*). Factors influencing the occurrence of overland flow are in general:

- The slope of land surface;
- The infiltration capacity of the soil;
- The depth of groundwater level.

Fig. 2.3. The effect of overland flow near Uithuizen.



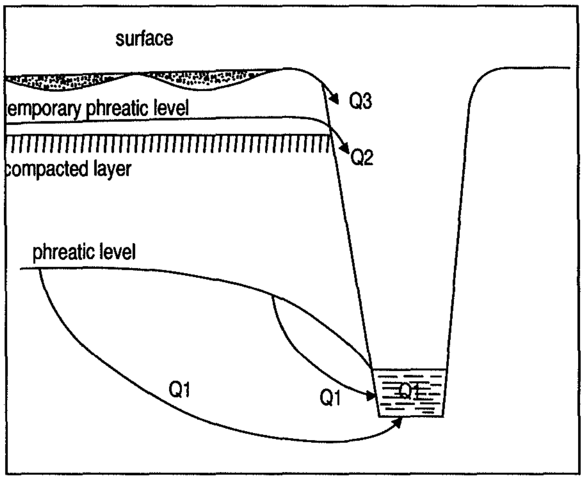


Fig. 2.4.. Discharge from the shallow soil (Bon, 1968).

Land slopes in the Netherlands are usually smaller than 2%; Fonck (Thunnissen, 1987b) stated that the minimum slope required for the occurrence of a significant amount of overland flow is 4%. Hence, land slope will not be the primary cause of overland flow. Also, the infiltration capacity of the soil in sandy regions can cope with normal rainfall intensities; this will not lead to overland flow. However, the infiltration capacity may decrease if a part of the soil is compacted and surficial discharge of water may occur at such places, e.g. where the soil was non-intentionally compacted by ploughing or by the wheels of heavy machinery. Ponding of the land occurs mainly in regions where groundwater levels reach the surface in winter periods because of a less pervious layer or a concave topography. In the winter season a ponding of the land, which is often discharged by temporary furrows, or by other means, can be observed in parts of the sandy regions too.

Interflow is the horizontal flow of water through the unsaturated soil towards a means of drainage, e.g. above a compacted layer. In the Netherlands, only a relatively thin unsaturated layer is present, but nevertheless, Bon (1968) affirmed the existence of interflow in the drainage basin of the Lunterse Beek. The effect of a discharge by shallow tile drainage is comparable to interflow. Tile drainage is a common feature in the clayey and peaty soils of the Netherlands. At present, it is also applied more and more to the sandy regions. The drain pipes are normally laid below the phreatic level in winter periods. With regard to a determination of the groundwater recharge of deeper layers, it is, practically speaking, useful to combine interflow and shallow drainage, not only because their effect will be the same, but also because a distinction is hardly possible.

Systematic studies quantifying the amounts of surficial discharge components are hardly available. Bon (1968) stated that surficial flow in the Lunterse Beek area discharged roughly 40% of the precipitation in a winter period. Thunnissen (1987b) summarized the findings of a number of Netherlands investigations, concluding that a surficial runoff of 10 to 30% of the annual rainfall excess was likely to occur in the Netherlands sandy regions.

2.1.4 Groundwater flow in the aquifer system

In sandy soils, where aquifer flow participates in the discharge of rainfall excess, the groundwater flow is initiated by groundwater recharge. Areas where the rainfall excess is predominantly discharged by groundwater transport are called areas of natural recharge. The average amount of downward vertical flow at the phreatic level corresponds to the average value of recharge. At deeper levels, also horizontal flow will take part in the discharge, implying a decreasing vertical velocity with depth. Knowledge of the flow patterns will lead to an insight in the travel times within the soil and in the age distribution in groundwater of the saturated subsurface.

Regional isohypses, valid for the Netherlands, are given in *Fig. 1.9*, showing the direction on a large scale of horizontal flows of groundwater. Discharge areas can take the form of a stream valley, but even large regions, where shallow groundwater receives a diffuse flow from below, can act as seepage zones. The situation will most evidently be more complicated in such areas than is suggested by *Fig.1.9.* In the upper layers a downward flow will prevail, but the deeper groundwater will flow predominantly upward. Differing isohypse patterns in shallow and deep groundwater flow are represented in *Fig.2.5.* Between the two sub-aquifers, a semi-confining clay layer with a large hydraulic resistance is present. The shallow groundwater is recharged by rainfall excess and by upward seepage from below; it is discharged by a well-developed stream system, as shown by the pattern of the shallow groundwater isohypses. The isohypses valid for the deeper sub-aquifer have a more regular pattern, indicating a diffuse discharge by an evenly distributed upward seepage. The flow in the deeper sub-aquifer will have an upward vertical component, whereas the most shallow groundwater will flow downward. The lower limit of the downward flow will depend on the particular hydrological situation. If considered in detail, the local flow patterns in groundwater will show a large variation. The local flow situation has to be taken into account when interpreting groundwater tritium data.

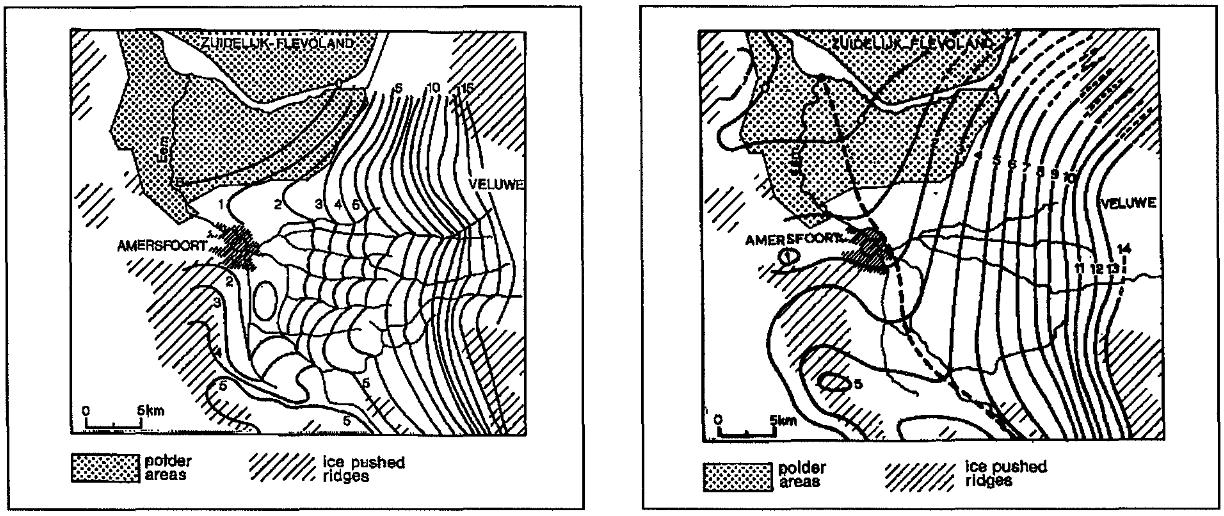


Fig.2.5 . Shallow and deep groundwater contours in a sandy discharge area (Gelderse Vallei).

The direction and the rate of groundwater flow may change by pumping. The shallow groundwater flow is affected near a well field, yet the vertical components remain roughly the same in the surrounding areas. However, at the identification of the various contributions to the flow in streams, or other surface water in sandy areas, the groundwater abstraction by pumping wells has to be taken into account. The pumped water will not reach the open-water draining in a natural way. The groundwater contribution to the stream flow has to be reduced accordingly. An estimate of the total of groundwater abstractions in sandy regions of the Netherlands amounts to approximately $1000*10^6$ $m^3 \cdot a^{-1}$. If that volume of water is equally distributed over the area of the sandy regions, it would represent a water depth of roughly 50 $mm \cdot a^{-1}$.

2.2 Horizontal and vertical flow components

2.2.1 Fluctuations in recharge

Apart from the annual fluctuations in rainfall excess, an even stronger variation will occur during the year due to seasonal fluctuations in actual evapotranspiration. The rainfall excess is almost zero in the summer months and nearly equal to precipitation in the winter months. However, the seasonal variations in rainfall excess need not lead to equally strong variations in the flow components of the groundwater in the saturated zone. On the contrary, there is good reason to assume that the vertical flow in the saturated zone will, with regard to the flow rate, but also concerning its composition, be nearly constant throughout the year:

1. The general stability in form of the patterns in isohypses throughout the year implies that internal flow components in groundwater are relatively constant.
2. Mook (1989) indicated that measured ^{18}O levels in fresh groundwater of rainfall recharged areas are often comparable to average rainfall. The ^{18}O, and also the tritium, levels in groundwater in cases where mini-screens were used are equal to average annual levels in local rainfall. These observations signify that proportional parts of all amounts of rainfall contribute to the groundwater recharge.
3. Investigations in the UK (Gardner, 1991) have established that in cases of a not too shallow groundwater level, a zero flux plane (ZFP) exists in summer. The ZFP divides an upper zone of upward flow to the plant roots and a lower zone, where the water is still flowing downward. Water balance studies of the lower, permanently drained, zone led to the conclusion that in cases of a well-developed soil and a pervious subsurface, the groundwater recharge was relatively constant.
4. Multilayer sampler investigations by RIVM at nine farms (Krajenbrink et al.,1989) indicated a practically constant groundwater composition in the upper two metres, whereas the input of water and minerals at land surface is clearly seasonal.

Individually and in several cases, the above arguments are liable to discussion. Nevertheless, the assumption of a constant downward flow of regularly distributed parts of the average annual rainfall provides, in general, an acceptable initial approach for the groundwater flow in the saturated zone.

The local rainfall excess will vary in cases with a spatially variable evapotranspiration. The differences will lead to varying patterns in groundwater recharge. For example, in years with small amounts of precipitation, the recharge in forest areas may be nearly zero, whereas for bare soils the recharge will be reduced, but not absent. There is usually high portion of open space in Netherlands' forests, resulting in variable flow situations.

2.2.2 Analytical approach of shallow flow

A. Single unconfined aquifer

The scheme in *Fig. 2.6* shows in cross-section the right half of a long strip of land, bordered by parallel draining water courses. At the same time, it may depict a circular island surrounded by open water. The scheme also represents many cases of regional groundwater flow in the Netherlands. Regional groundwater isohypses, indicating the flow towards the boundary between groundwater recharge areas and areas of discharge, are often virtually parallel lines. The situation in such an area is similar to the scheme in *Fig. 2.6*, except near the boundary. When the isohypses have a curvilinear form, as may occur when the discharge zone has a concave form, the situation resembles the flow in the soil of a circular island, again, except near the boundaries. The scheme in *Fig. 2.6* suggests the presence of a single unconfined aquifer, which is homogeneous and isotropic. In field situations, a detailed description of the subsurface will always reveal a heterogeneous and anisotropic character of the sediments. However, when considering the problem at a regional scale, the actual flow will closely resemble the schematic flow (under homogeneous and isotropic conditions).

In evaluating travel times of water from the phreatic level to a place (x,z) in the subsurface the differential equation describing the flow pattern has to be solved. For a single unconfined aquifer under a long strip, bounded by parallel water courses, the equation and the boundary conditions are:

$$\partial^2h/\partial x^2 + \partial^2h/\partial z^2 = 0,$$

$$h(L,z) = 0; \qquad \partial h/\partial x\,(0,z) = 0;$$

$$\partial h/\partial z\,(x,D) = 0; \qquad \partial h/\partial z\,(x,0) = I/k;$$

where: x,z = coordinates (m), covering a cross-section;
h = h(x,z) = the head (m) above reference level;
D = thickness of the aquifer (m);
I = a constant groundwater recharge ($m{\cdot}day^{-1}$);
k = permeability ($m{\cdot}day^{-1}$).

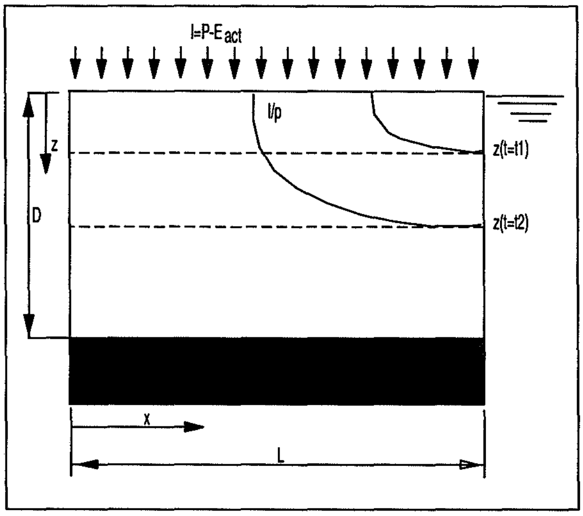


Fig. 2.6. Travel times in the soil according to Bruggeman (in press).

The equation can be solved with the help of a finite Fourier transformation (Bruggeman, in press). The travel times in the vertical direction follow from the equation of the flow function, which can be derived from the equations:

$$\partial x/\partial t = -k/p * \partial h/\partial x; \qquad \text{and:} \qquad \partial z/\partial t = -k/p * \partial h/\partial z$$

where: p = effective porosity (dimensionless);
t = travel times (days).

The solution for an infinitely long strip and for a circular island (Bruggeman, in press) is:

$$z = D*\{1-\exp[-I*t/(p*D)]\} \text{ and } t = (p*D/I)*\ln D/(D-z);$$

Neither the permeability, k, nor the horizontal dimensions play a role in the equation describing travel times. The planes of equal travel times are horizontal (*Fig. 2.6*). The solution does not hold for distances of less than D from the draining water. For draining water courses not fully penetrating the aquifer, the minimum distance is 3*D.

B. Multilayered aquifers

In the Netherlands, where the shallow subsurface contains fluviatile sediments, the aquifer system often consists of an intercalation of permeable and less permeable layers. In the case of relatively high resistances of semi-permeable layers, the aquifer becomes multilayered and the groundwater in the deeper layers may reach a higher age than in the case of a single aquifer. For a two-layered system (*Fig. 2.7*), an approximative solution with regard to the travel times can be reached in solving the potential problem, governed by the appropriate equations and boundary conditions:

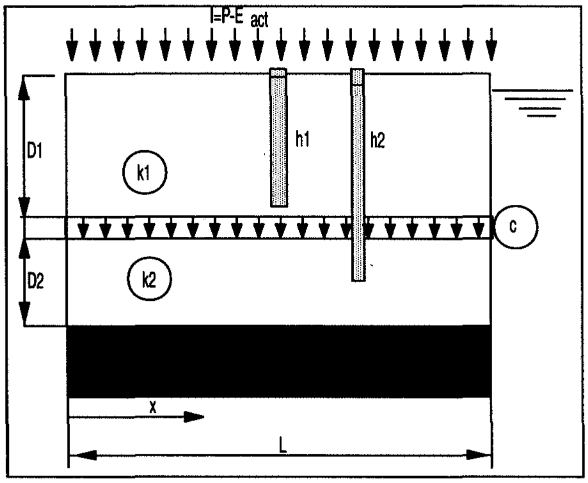


Fig. 2.7. Scheme of a two-layered aquifer system.

$$d^2h_1/dx^2 - a_1(h_1 - h_2) + I/(k_1{*}D_1) = 0;$$
$$d^2h_2/dx^2 + a_2(h_2 - h_2) = 0;$$
$$\text{at } x = 0: \quad dh_1/dx = 0; \qquad \text{at } x = L: \quad h_1 = 0;$$
$$dh_2/dx = 0; \qquad h_2 = 0;$$

where:

$a_1=1/k_1D_1c$; $a_2=1/k_2D_2c$; (sqrt(k_1D_1c) and sqrt(k_2D_2c) are leakage factors).

The solution (Bruggeman,in press) has the form of equations describing the heads in the upper and lower aquifer:

$$h_1 = I/k_1D_1{*}a_1/(a_1+a_2)^2{*}\{1-\cosh(x{*}\mathrm{sqrt}(a_1+a_2))/\cosh(L{*}\mathrm{sqrt}(a_1+a_2))\}+ I/2(k_1D_1){*}a_2/(a_1+a_2){*}(L^2-x^2)$$
$$h_2 = -I/k_1D_1{*}a_2/(a_1+a_2)^2{*}\{1-\cosh(x{*}\mathrm{sqrt}(a_1+a_2))/\cosh(L{*}\mathrm{sqrt}(a_1+a_2))\}+ I/2(k_1D_1){*}a_2/(a_1+a_2){*}(L_2-x_2)$$

and:

$$h_1-h_2=I/k_1D_1{*}1/(a_1+a_2){*}\{1-\cosh(x{*}\mathrm{sqrt}(a_1+a_2))/\cosh(L{*}\mathrm{sqrt}(a_1+a_2))\}$$

In regional problems, the value of L*sqrt(a_1+a_2) will often be large because the horizontal dimensions are mostly large in comparison to the leakage factors. For large values of L*sqrt(a_1+a_2) and x<<L (in the central part of the region), it can be derived that the quotient of the cosh terms approaches zero. The percolation through the resisting layer is:

$$q_z = (h_1-h_2)/c = I * k_2D_2/(k_1D_1 + k_2D_2),$$

hence, the downward percolation has a constant value, implying a constant recharge, similar to the situation in the upper aquifer. Moreover, if the values of k_1 and k_2 are equal, it can be derived that the vertical percolation through the resisting layer is equal to the downward percolation at the same place in a single aquifer. Hence, in such cases also the age distribution within the groundwater of deeper layers may be determined as if both sub-aquifers constituted one single aquifer.

For large values of transmissivity of the upper layer and a large hydraulic resistance, the value of L*sqrt(a_1+a_2) will become small; in this case the total vertical percolation over the full width of the area, may, according to Bruggeman (l.c.), be approximated by:

$$q_z = I{*}L^3/3k_1D_1c$$

In the latter case, no simple relation can be derived with regard to the age distribution of the groundwater in the deeper aquifer. In situations with small values of L*sqrt(a_1+a_2), numerical methods should be applied for the dermination of the travel times.

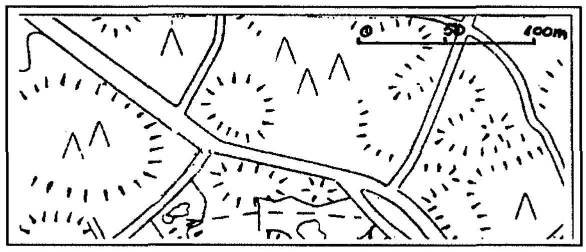
2.2.3. Numerical methods to simulate heterogeneous recharge situations

A. Variations in space

The stream function in groundwater hydraulics describes a set of stream lines, which are orthogonal to the equipotential lines belonging to the potential function (under isotropic conditions). The stream function also obeys the Laplace differential equation. If the appropriate boundary conditions are applied, the problem is fully defined and can be solved in the sense that a stream function is determined (Van den Akker, 1982). Practical problems often have to be solved by numerical approximation. A useful tool to determine groundwater flow patterns and the resulting travel times for a varying groundwater recharge and under varying geohydrological conditions is the program, FLOP3N, developed by Veling (1991). FLOP3N (**FL**ow **P**attern; **3**-dimensional; **N**-layers) is a particle tracking program for a system of homogeneous anisotropic layers, in which partially penetrating wells may be active.

There are areas in existence where the local rainfall excess varies because the vegetation changes over short distances. The forest shown in *Fig. 2.8* consists of zones planted with trees where the evapotranspiration will be large, and where forest lanes with no

Fig. 2.8. Forest area, with open spaces.



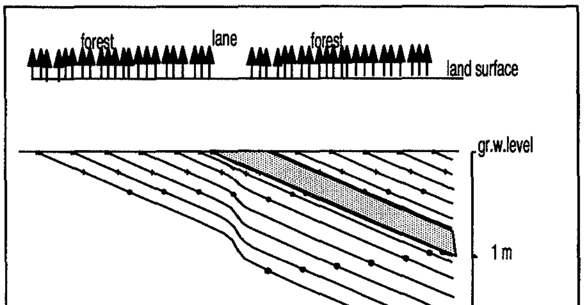
marked vegetation and a low evapotranspiration occupy 8% of the area. The downward percolation is a function of the average groundwater recharge. The situation can be elucidated by means of a groundwater flow simulation using the model FLOP3N. A strip of forest, with a length of L = 125 m, an infinite width B and situated in the direction of flow, is represented. The additional groundwater recharge, Q, in the forest lanes can be derived by assuming that:

P = the long-term average annual rainfall; $P = 0.80\ \mathrm{m{\cdot}a^{-1}}$;
E_o = average annual open water evaporation: $E_o{=}0.67\ \mathrm{m{\cdot}a^{-1}}$;
hence: $\mathbf{Q = 5*10*[(P-0.4*E_o)-(P-E_o)] = 0.0534\ m^3{\cdot}day^{-1}}$.

The extra recharge is simulated by the introduction of small recharge wells at distances of 5 m, situated at the phreatic level and placed in parallel rows, transsecting the strip at regular intervals of 125 m, representing forest lanes with a width of b = 10 m (=8%). The natural flow of groundwater corresponds to a gradient in heads of 1:1000 and a hydraulic transmissivity kD = 6000 $\mathrm{m^2{\cdot}day^{-1}}$ (See *Fig.2.9* for an elaboration).

The results indicate the relatively small disturbances in the flow pattern near forest lanes; at some distance the pattern again resembles the average pattern. In *Fig. 2.9* a distorted scale was used. A non-distorted scale, as in *Fig. 2.10*, shows that the zone containing water recharged in the lane only occupies a small strip. The recharge in forest lanes has a chemical composition deviating from an average forest recharge. The zone with a deviating composition becomes negligible at greater depths. Observation wells are mainly situated near forest lanes. In such cases, the flow pattern may deviate from the average flow pattern, but the sampled groundwater will largely consist of forest water.

Fig. 2.9. Groundwater flow lines, distorted scale, cross-section along flow.



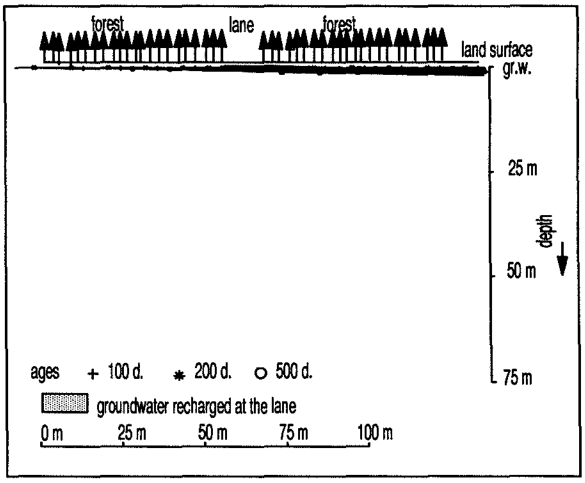


Fig. 2.10. Groundwater flow lines; no distortion of scale, cross-section along flow.

B. Variations in time

Due to variations in meteorological conditions, the rainfall excess may vary from year to year and, therefore, also the groundwater recharge. Consequently, the initial downward percolation will vary. For a homogeneous vegetation, the changes in the vertical velocity can be considered as fluctuations around an average value and the corresponding travel times as a result of the average groundwater recharge.

The variations in time of groundwater recharge in areas with a mixed vegetation may lead to temporary variations in the flow direction. The result can be a changing origin of the groundwater pumped at observation screens and fluctuations in the composition of pumped water, as is often observed (Duijvenbooden, 1985). Such a situation may occur in cases where groundwater flow is in the direction of the length of a forest lane or a similar open space. The flow patterns can again be simulated by FLOP3N. The numerical simulation concerns cases of groundwater recharge, not only different between the forest area and forest lane, but also, where in the course of time changes occur in the difference between both types of recharge. The groundwater recharge is I_f $\mathrm{mm{\cdot}a^{-1}}$ in the forest area and in the open forest lane $I_{o.s.}$ $\mathrm{mm{\cdot}a^{-1}}$. Assuming that a forest lane has a width of 5 m, taking into account the shadow of the canopy, the assumed additional recharge values are:

year-1: $I_{o.s.}-I_f = 200\ \mathrm{mm{\cdot}a^{-1}}$;
year-2: $I_{o.s.}-I_f = 100\ \mathrm{mm{\cdot}a^{-1}}$.

The flow situations for two different years were simulated with the model FLOP3N by taking a strip of L = 300 m and an infinite width, B, in the direction of flow. The lane is represented by a row of imaginary re-

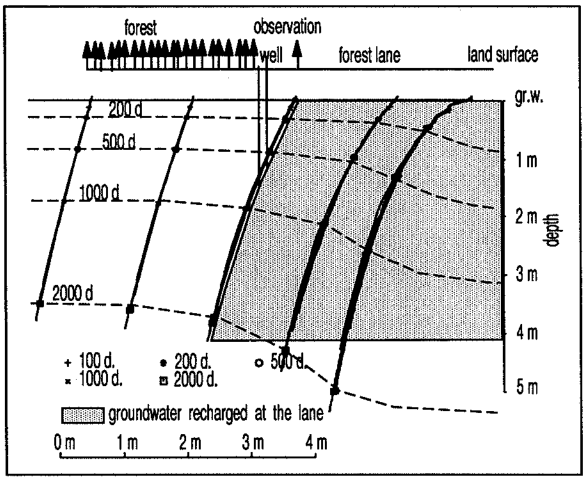


Fig. 2.11. Projection of flow lines in a cross-section; natural flow in the direction of the lane; large differences in recharge

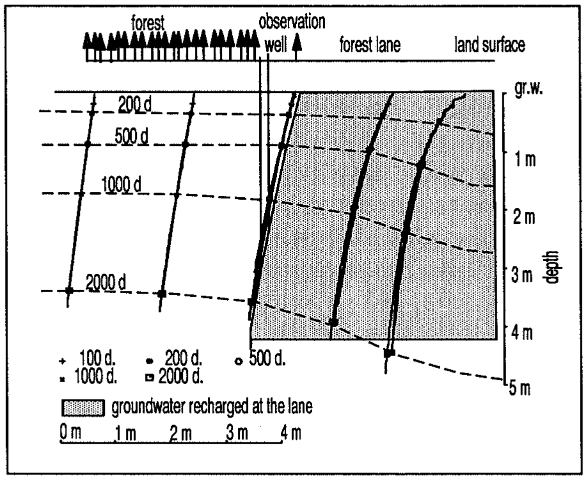


Fig. 2.12. Projection of flow lines in a cross-section; natural flow in the direction of the lane; small differences in recharge.

charge wells, delivering an amount of water equal to the difference in recharge between forest and open space. The natural groundwater flow in both years corresponds to a gradient in head of 1:750 and a transmissivity of the subsurface of kD=750 $m^2 \cdot day^{-1}$. For both cases, the downward percolation of the open-space water, projected at a plane perpendicular to the direction of flow, is given in *Figs 2.11* and *2.12*, showing half of the lane and the adjacent forest area. Flow patterns near the well deviate from the average pattern in the same way as indicated in Fig. 2.9. However, the open space water occupies another area in the subsurface because the flow is in the direction of the lane. The zone with open space water is larger than just the soil below the forest lane and increases when the additional recharge in the forest lane increases. Assume that an observation well, with a set of screens, is placed at the boundary of lane and forest. The origin of pumped groundwater for a number of screens will differ, implying a different composition.

Hence, if samples are collected on two different dates, not only will the composition show a variation related to depth on the same date, but changes in time may also occur. A natural situation may show an even more complicated configuration than the simulated case. In the above example, the annual recharge has been taken as a base. Different flow patterns will also result if seasonal fluctuations are of influence (no Zero-Flux-Planes).

2.3. Basic considerations in groundwater recharge

The average long-term precipitation in sandy regions is in the order of 800 $mm \cdot a^{-1}$. The average long-term reference evapotranspiration is roughly 550 $mm \cdot a^{-1}$, which also represents the potential evapotranspiration for grassland. Hence, the groundwater recharge if no disturbing factors are present is I = 250 $mm \cdot a^{-1}$, implying an average downward vertical velocity of roughly I/p = 700 $mm \cdot a^{-1}$ (assuming that the porosity p = 0.35). Disturbing factors in areas with a relatively deep groundwater table are the application of sprinkling water and/or the reduction in the potential evapotranspiration due to soil water deficits in the summer period. Both factors lead to an increase in groundwater recharge, which at deep groundwater tables, may be more than 100 $mm \cdot a^{-1}$ (section 2.2.2). Hence, the expected downward velocity in grassland is in the order of 1 $m \cdot a^{-1}$.

In areas with a shallow groundwater table surficial discharge components may remove a part of the rainfall excess, be it because the area is a seepage zone, or because of the presence of less pervious shallow layers. The remaining recharge of the saturated groundwater decreases accordingly, implying a smaller downward percolation. The factors determining the volume of surficial discharge components, like overland flow, interflow and tile drainage, are poorly known. It is hardly possible to measure the occurrence and the magnitude of surficial discharge components, and, therefore, also the groundwater recharge cannot be predicted in such cases. On the other hand, if the groundwater travel times and the vertical velocity in shallow layers can be determined, a value for the recharge can be derived and possible surficial discharge components can be estimated.

There is good reason to assume that the downward velocity of groundwater in the saturated subsurface is often relatively constant throughout the seasons. Equal parts of the average annual rainfall, including the summer precipitation, flow downward during all seasons. Hence, seasonal effects may initially be ignored.

For the hydrological scheme, representing the majority of regional groundwater flow situations, an analytical equation can be derived which describes the vertical flow of groundwater in the upper aquifer. A major feature of the equation is that the permeability and the horizontal dimensions of the groundwater body are not represented. As a consequence, other aspects of the geohydrological situation need not be known in full detail; only the aquifer depth and the recharge determine the downward groundwater velocity. An important implication of this analytical solution is that the isochrones (planes of equal age) are horizons, which are situated parallel to land surface.

The situation within forested areas is often characterized by a non-homogeneous recharge. A suitable way to simulate the flow situation is to make use of numerical models. The FLOP3N approach may indicate disturbances in the flow situation. if compared to the average situation in a forest area. The groundwater ages will deviate near forest lanes and other open spaces. Moreover, also the groundwater composition may have different features, especially if a forest lane is in the same direction as the groundwater flow. The flow situation near forest lanes is of special interest because, for practical reasons, observation wells are often situated near a forest lane.

The conclusions to be drawn from the general considerations with regard to the set-up of investigations on groundwater recharge and travel times follow:

1. Methods which are well suited to determining a downward velocity in the order of magnitude of 1 $m \cdot a^{-1}$ should be used.
2. The vertical flow of groundwater in the saturated zone is relatively constant and, also, the downward percolating amounts of water forming the average annual precipitation are equal.
3. In cases where surficial discharge components may remove part of the rainfall excess, estimating the amount of groundwater recharge is difficult; therefore, the determination of groundwater ages by isotope methods represents the most reliable way to estimate the groundwater recharge.
4. When investigating the groundwater recharge and the downward percolation in forest areas, the direction of the horizontal groundwater flow, and the situation of the observation well relative to open spaces and to areas with a dense vegetation, should be taken into account.

3. OVERVIEW OF METHODS AND TECHNIQUES

3.1. Hierarchy of the investigations

The fate of diffuse contaminants in soils of sandy regions is determined by the shallow groundwater flow and travel times resulting from the local hydrological conditions. Various methods of investigation to explore the groundwater situation in different regions will be described. Groundwater can only be investigated by means of local measurements. The results of local studies had to be combined to constitute regional surveys, which, finally, were integrated in a national review. Methods were developed to extrapolate the results of local studies to a regional and, ultimately, the national level.The sequence of studies at various levels comprised:

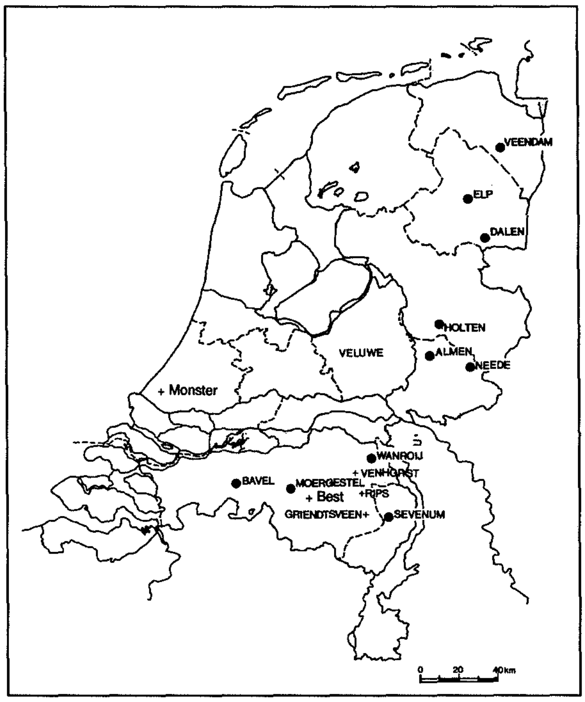
a. Local geohydrological investigations (5 to 50 ha), resulting in a detailed evaluation of the situation;
b. Regional surveys (with areas in the order of magnitude of 1000 km^2), combining the local studies and using data from the National Groundwater Quality Monitoring Network;
c. Extrapolation to the national scale (the sandy regions of the Netherlands), using GIS methods.

A. Local investigations
Detailed field investigations (*Fig. 3.1*) were realized at 16 locations, in which the determination of groundwater ages, based on the tritium contents in a series of observation screens, was always included. The principles of groundwater dating by tritium methods are explained in Chapter 4. In each particular field study, a hydrological investigation was carried out, applying techniques often used in groundwater studies, but also specific methods aiming at a reconnaissance of the shallow soil:

1. A sedimentological study of the soil, based on cored boreholes to a depth of roughly 8 m, was carried out at ten farms. At the Best test location, 12 Ackermann drillings were made to a depth of 25 m. The set-up of the sedimentological investigations is discussed in section 3.2.
2. A grain size analysis was carried out at locations in the Peel region and in Best.
3. Three to twelve geo-electrical surface measurements (VES) were executed at all locations using an ABEM Terrameter and a multicore cable proposed by Barker.
4. Electromagnetical surveys with the Geonics EM-31 were performed, covering the local areas of study. Geophysical methods are further discussed in section 3.3.
5. Groundwater levels were determined in shallow boreholes drilled by hand, but also in deeper observation wells. By surveying the wells and boreholes, the observations could be related in the form of isohypses.
6. At some of the locations, a detailed survey, investigating the groundwater contents of the stable isotopes ^{18}O and ^{2}H, was realized in order to determine the possible occurrence of open water evaporation.
7. A large number of analyses on the chemical composition of the groundwater were carried out (see also section 3.4):
   a. on samples from shallow boreholes;
   b. on samples from observation wells;
   c. on samples from so-called multi-layer sampler arrangements, installed at nine farms investigated (Krajenbrink et al., 1989).

B. Regional surveys
The regional investigations were based on the interpretation of local studies, but also on two other types of investigations:
- In 1983 and 1984, the screens of the wells in the National Groundwater Monitoring Network

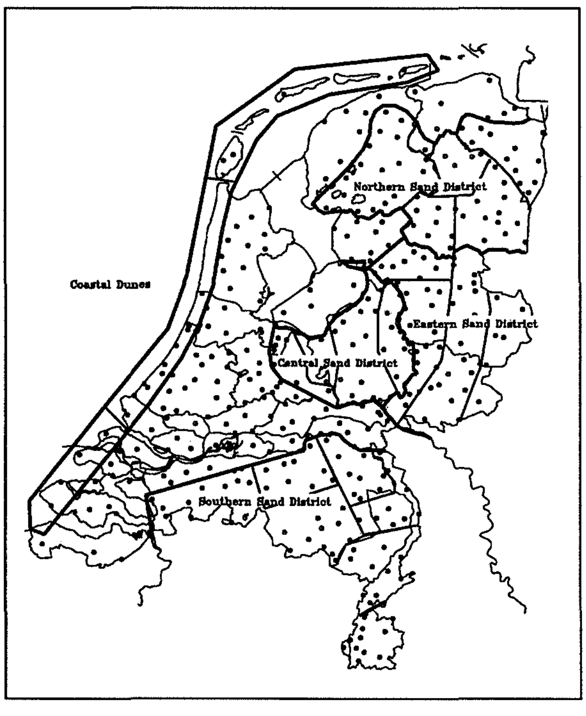
Fig. 3.1. The locations of the detailed hydrological investigations.



(LMG) were systematically sampled to determine the tritium contents. In 1990 and 1991, the province of Gelderland installed a groundwater quality monitoring network (PMG), additional to the national system. The screens of these wells were also sampled and the water analyzed with regard to its tritium content. The interpretation of tritium data, collected from the monitoring wells, in combination with other available data, resulted in a review of the regional situation.
A number of local groundwater studies in the Veluwe region were combined. Additionally, the man-made springs ("sprengen") were investigated. The interpretation of tritium data in samples taken from the sprengen was used to determine the age distribution of the inflowing groundwater. But also the chemical composition of samples from sprengen and groundwater was analyzed and evaluated, aiming at determining rainfall condensation factors before the rainfall excess recharged the groundwater. The calculations resulted in estimates on the groundwater recharge in the upstream areas, consisting of heathlands and forests.

The wells of the National Groundwater Quality Network, were subdivided according to their location in the major sand districts of the Netherlands and in the smaller regions (*Fig.3.2*) which were used for a national inventory (Cramer, 1982). The inventory was supported by regional geohydrological surveys carried out by various institutes. Apart from a description of the hydrogeological situation, many of these regional studies contained the elaboration of a long-term water balance for the region concerned, giving estimates of the magnitude of groundwater recharge. Moreover, the various sheets of the Groundwater Map of the Netherlands, compiled by DGV-TNO, contain useful information on the general hydrological situation of the various regions.

Fig. 3.2 Monitoring wells in the sandy areas, divided in geohydrological districts and smaller regions.



C. Extrapolation to the national scale using GIS methods
The detailed investigations, as well as the regional surveys, were elaborated in order to draw conclusions about the factors determining groundwater recharge and the resulting travel times of shallow groundwater. Many of the elements related to groundwater flow and travel times are represented in a Geographical Information System (GIS), available at RIVM. The GIS system was used to generate data on precipitation, on actual evapotranspiration and on groundwater recharge, depending on the local vegetation and the local soil type. Finally, the resulting values of groundwater recharge were combined with soil and subsurface data to determine groundwater travel times.

3.2. Sedimentological surveys of the shallow subsurface

Research of groundwater flow patterns in the subsurface with regard to their environmental impact requires the development of appropriate investigation techniques. A reconnaissance of the sedimentation environment of the shallow soil is possible with sedimentological methods, an advantage being that the collection of undisturbed samples from shallow layers can be done by relatively simple means. The availability of undisturbed samples is needed for a sedimentological analysis of the structures in subsurface layers, which originated during deposition. The analyzed sediments, belonging to Upper Pleistocene formations, were deposited under varying conditions. Sedimentation occurred predominately by local streams and aeolian forces in alternatingly cold (glacial) and warm (interstadial) periods. Sedimentary structures changed by the action of secondary phenomena related to cold periods (e.g. cryoturbation). Hence, the observed layers necessitate a detailed sampling. If properly interpreted, the observed structures will yield information on the depositional environment and on other geological features of the soil.

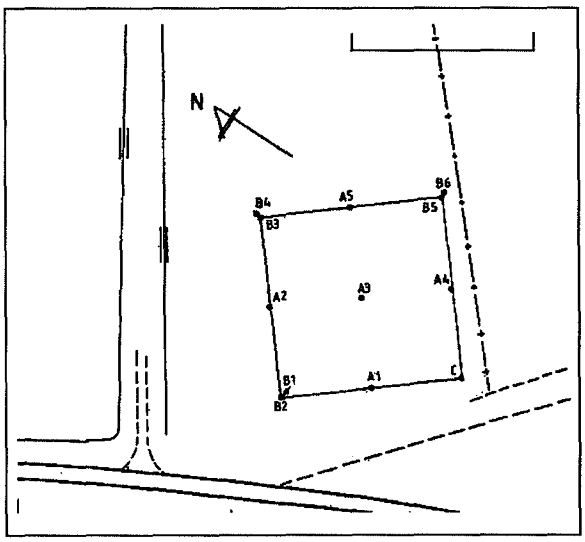
The sedimentological studies resulted in:
a. A detailed geological description of the site;

b. An indication of the areal extent of the layers discerned;
c. Detailed information concerning lithological features.

There were two techniques used in the sedimentological studies:
- detailed fieldwork was carried out at the Best location, including drillings by a contractor to a depth of 30 m, providing undisturbed soil samples;
- the technique used at ten investigated farms in the sandy regions consisted of hand drilling of boreholes to a depth of roughly 8 m using a simple apparatus. This simpler approach provided relatively undisturbed samples over the full drilling depth.

The project on spatial variability of soil features at the Best location was based on 12 drillings, where cored samples were taken to sedimentologically describe the soil deposits. The realization was as follows:
- The drillings were placed in a square of 40m x 40 m at varying distances (*Fig. 3.3*) to investigate the lateral extent of the various sedimentological units. The drillings, 20 to 30 m deep, were carried out by a contractor using the Ackerman system under supervision of the Laboratory of Soil Mechanics (LGM) at Delft. Undisturbed cores, with a length of 30 cm and a width of 10 cm, became available, which, after delivery at the RIVM, were cut in two half-cylinders (Van Alphen, 1984). The samples were provisionally described, indicating color, grain size, form and structure of the deposits, and the presence of organic material. Thereafter, lacquer peels were made of the central plane surfaces, originally in the middle of the cylinder. The lacquer peels were fixed on to plates, such that each plate showed one metre of samples

Fig. 3.3. Location of the cored drillings in Best.



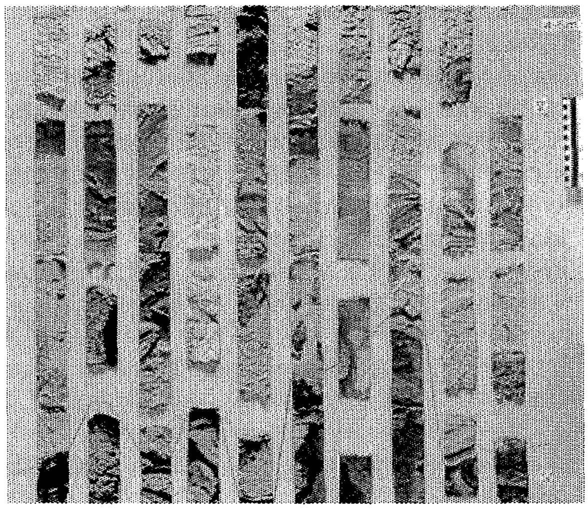


Fig. 3.4. Structure of the layers from 4-5 m in the soil of the Best site (see also section 5.2).

from the same depth of the various drillings (*Fig. 3.4*). The analysis of sedimentological structures was based on the examination of the lacquer peels.

The remaining samples were analyzed by the RIVM Soil Laboratory for organic carbon content, Cation Exchange Capacity (CEC), soil pH, grain size distribution, median value of grain size (M figure) and sorting. These features were also considered in the sedimentological analysis. All data were subjected to a geostatistical analysis (Gerringa and Obdam, 1985).

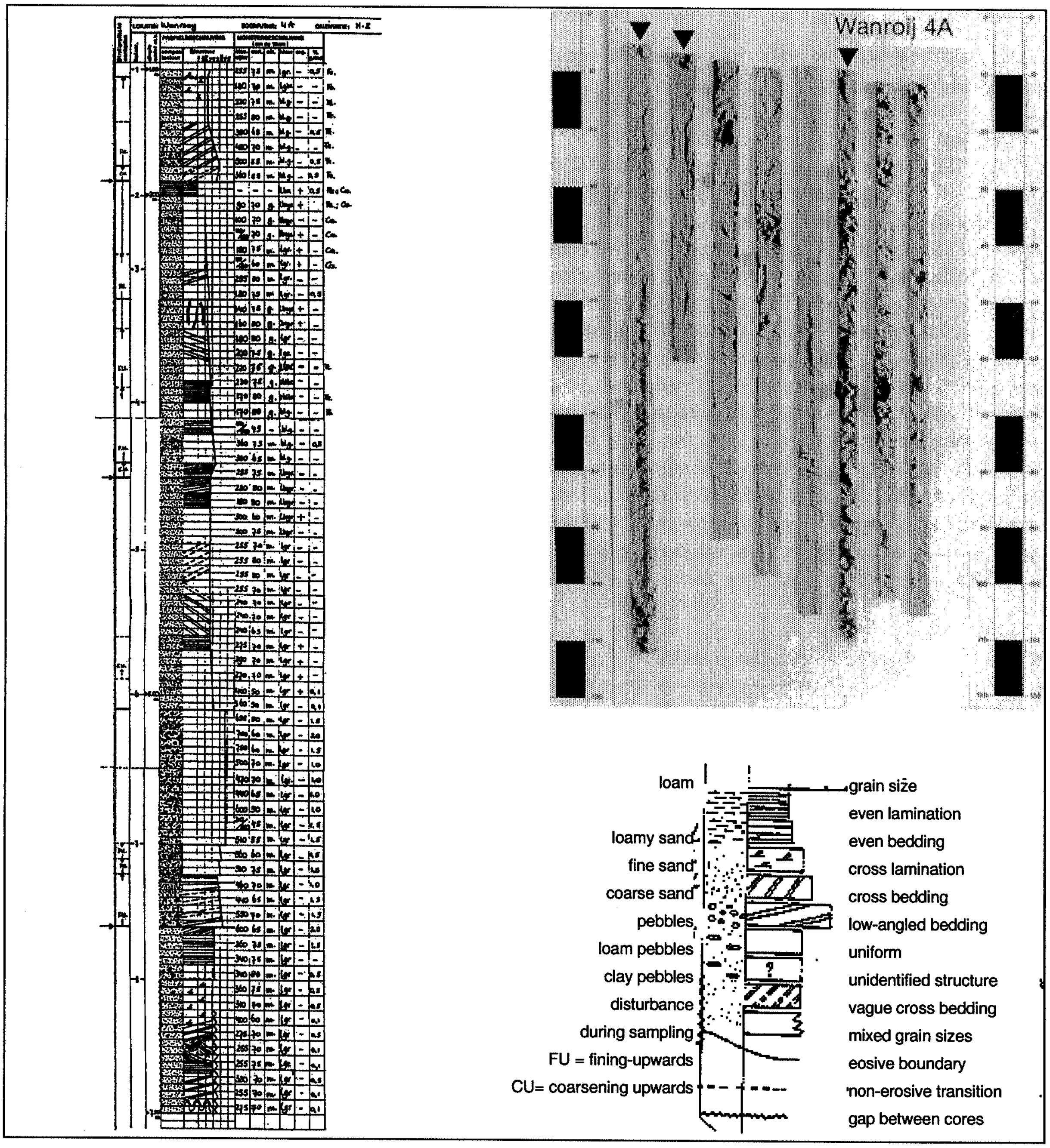
The investigations of the shallow subsurface at ten farms in the sandy areas of the Netherlands aimed at a study of nitrate concentrations resulting from the application of fertilizer and manure. A main element of the investigations was the sedimentological analysis of the shallow subsurface. The samples were taken by drilling some ten boreholes to a depth of roughly 8 m with a Van der Staay suction corer (Van de Meene, 1979). The cored boreholes were regularly distributed over the farmland investigated. The method was as follows: the drilling team brought a two-inch PVC pipe into the saturated soil by lowering the soil pressure at the bottom of the pipe as the pipe went down. This was done by the manipulation of a leather seal at the top. After the soil was pierced a few metres by the pipe, the pressure was fixed and the pipe was lifted, such that it contained a relatively undisturbed soil sample. The hole was widened by cable-tool drilling to the depth already reached. Thereafter, the whole procedure was repeated to sample the next few metres of the soil. The pipes holding the samples were, after draining the excess water, cut in two halves. A lacquer peel was made of the central plane surface in the middle of the original sample, which was fixed to a plate. All samples from one borehole were shown on one plate (*Fig. 3.5*).

The lacquer peels were examined for a sedimentological analysis. The remaining material was subjected to quantitative determinations of soil parameters, like median grain size, sorting, organic and calcareous content. All data were combined into a description of the sedimentological structure of the drilled soil layers. Apart from a detailed geological description of the layers to a depth of 8 m, the sedimentological study resulted in:

- An indication on the permeabilities of the layers in shallow subsurface, leading to conclusions concerning groundwater flow.
  An evaluation of the possible occurrence of organic material in the subsurface, which was very helpful in explaining the observed nitrate contents in the soil.

Additional activities included the observation of groundwater heads, the analysis of water samples and the execution of geophysical measurements. The sedimentological results were combined with the results of the other investigations, leading to a detailed re-

Fig. 3.5 Results of the sedimentological analysis of drilling 4A from the farm investigated in Wanroij.



view of the local hydrological situation. One of the elements was the assessment of groundwater travel times by the determination of tritium contents in samples from a series of observation screens in one well. The review was used for the explanation of the observed groundwater composition, resulting from fertilization.

3.3. Geophysical methods in environmental soil studies

Geoelectrical measurements.

The ABEM Terrameter was selected as the basic instrument for geo-electrical measurements, in combination with a BGS-128 multicore cable (*Fig. 3.6*) developed by Barker (1971). The arrangement provided detailed Wenner series by carrying out Offset-Wenner and alternating pole readings. Applying the equations proposed by Telford (1976) to the measurements resulted in a Wenner series of values for distances of a=0.5m; 1m; 1.5m; up to 128m. The Wenner series yielded much information concerning the shallow soil layers. Interpretation was according to a method developed by Hemker (1988).

The resistivity r (in Ωm) of sand layers will approximately obey the equation (Archie's empirical formula):

r(layer) = F * r(water);

where r(layer) is the resistivity derived from the interpretation of the geo-electrical measurements. The resistivity of the groundwater, r(water), can be derived from the measured conductivity of samples. The relation between conductivity and resistivity is:

1000 / (conductivity in mS/m) = (resistivity in Ωm).

The groundwater temperature in situ will be lower than at the laboratory. In situ it will be about 10 °C, leading to a conductivity of 0.78 times the value at 20 °C. The factor, F, is called the formation factor; it is an intrinsic property of the sand layer concerned. For the subsurface of the Netherlands, DGV-TNO(1981) indicates the following as orders of magnitude: from

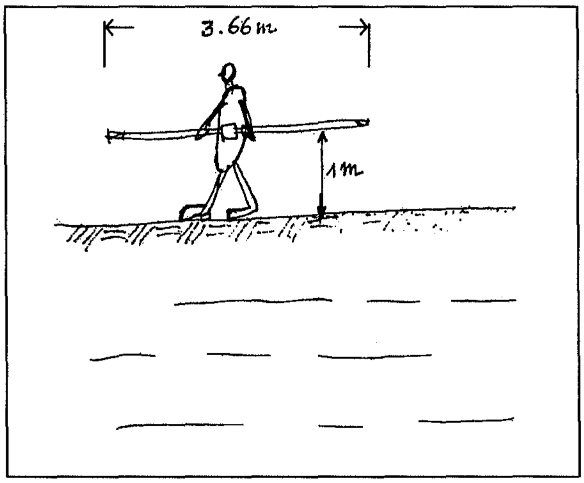


Fig. 3.7. Operation of the EM-31.

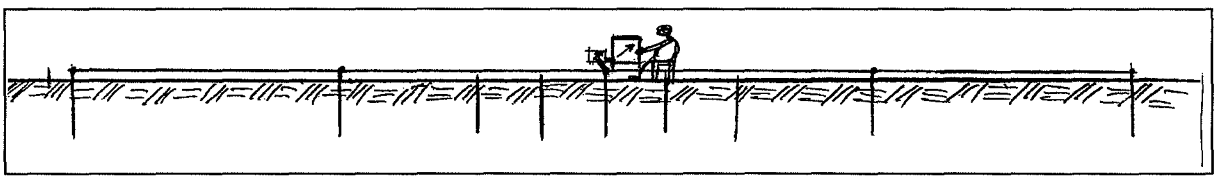
'Fine silty sand': F=3; to "Coarse sand without silt": F=5 and "Very coarse sand and gravel": F>5. By substituting the measured groundwater conductivities, the formation factors can be derived for the various layers distinguished. The formation factors also lead to conclusions on the soil structure.

Electromagnetical observations

The instrument used for the electromagnetic measurements was the Geonics EM-31. For the standard operating procedure, the operator uses a transmitter and a receiver coil at a fixed distance of 3.66m in a vertical position at roughly 1 m above land surface (*Fig. 3.7*). Values of the apparent conductivity of the soil down to a depth of approximately 6 m are obtained, which may be interpreted (McNeill, 1980) in the sense of major soil features (e.g. sand versus clay) of the top layers.

The geophysical surveys consisted of carrying out a limited number of geo-electrical measurements (VES) and a full areal coverage by EM-31 measurements of the investigated site. The VES were located in places where conductivity differences in soil and/or groundwater were expected and the EM survey indicated the areal extent of such varying situations. The interpretation of the EM measurements could be related to the VES observations since the VES have indicated the subsequent layers of the shallow soil with respect to electrical conductivity,

Fig. 3.6 Operation of geo-electrical surface measurements using the BGS-128 multicore cable.



depth and thickness. These data could be used to estimate the expected EM-31 values at the same location.

3.4. The relation between quality and quantity of groundwater

The constituents of the groundwater composition, analyzed in the investigations, consisted of the following parameters:

electrical conductivity (EC); acidity (pH); chloride (Cl^-); nitrate (NO_3^-); orthophosphate (PO_4^{3-}); total phosphate (P); sulphate (SO_4^{2-}); potassium (K^+); sodium (Na^+); magnesium (Mg^{2+}); calcium (Ca^{2+}); ammonium (NH_4^+).

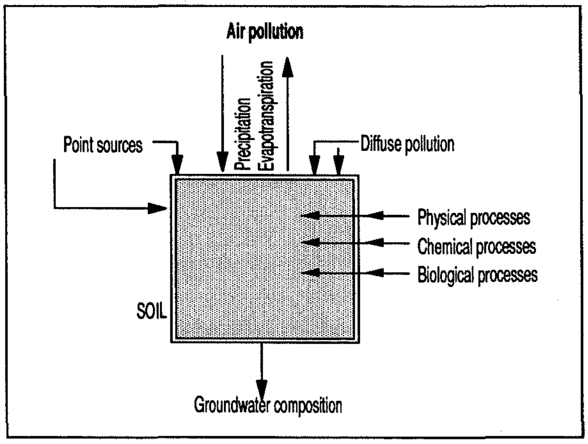


Fig. 3.8. Factors interfering at the groundwater composition

Sampling, transport and analyses were carried out according to normal RIVM procedures, unless stated otherwise. The multi-layer sampler method was proposed by Ronen et al. (1986); it is based on the dialysis of compounds through a semi-permeable membrane between groundwater and a series of sampling cells. The analyzed parameters belong to the major components of groundwater. The present interpretation of the observed chemical composition will mainly concern its hydrological implications. Yet, when the observed hydrological situation has a specific environmental impact, the relation will be elucidated with the help of the groundwater composition.

The starting point in considering the groundwater composition is the composition of the recharge, including an addition of chemical compounds derived from fertilizer, manure, etc. However, even if no compounds were added, soil processes will change the composition (*Fig. 3.8*) before the groundwater in deeper layers is reached. These processes represented schematically are:
1. Condensation by evapotranspiration, resulting in increased concentrations.
2. Physical, chemical and biochemical soil processes.

The condensation by evapotranspiration will affect all the chemical compounds dissolved in water, except the natural isotopes, being part of the water itself. The increase in concentration is the same for all constituents and equals the ratio between the original and the remaining amounts of water. This ratio depends on the magnitude of the actual evapotranspiration affecting the groundwater sampled. If the condensation factor can be estimated, also the evaporated part of the total amount of rainwater can be estimated. The element least affected by soil processes is the chloride ion. Hence, by preference, the chloride concentrations are used to estimate condensation factors and, thereby, the evapotranspiration. In cases where different condensation factors hold for various situations within one area, the corresponding groundwater can sometimes be recognized with the help of chloride concentrations or electrical conductivity.

The use of condensation factors to estimate the evapotranspiration is only possible if no disturbing addition of chemical compounds occurs. Strong effects of anthropogenic pollution result from an addition of chemical compounds by fertilizer or the deposition of manure slurry. The groundwater composition will assume concentrations clearly deviating from the composition in a non-influenced situation. Because this type of pollution often has a well-known start, the extent of the resulting polluted groundwater body may indicate hydrological processes involved.

4. INTERPRETATION OF TRITIUM DATA IN HYDROLOGY

4.1. Sampling and analysis of tritium levels

Travel times of water in the soil, being important from an environmental viewpoint, follow from an interpretation of the groundwater tritium levels. Groundwater dating based on tritium requires proper knowledge of the values in precipitation, because the groundwater levels have to be related to the original values at the sources. Before 1970, the tritium levels of precipitation in the Netherlands were only analyzed incidentally. After that, the precipitation was sampled both at the Centre for Isotope Research (CIO) of Groningen University and at the National Institute of Public Health and Environmental Protection (RIVM) in Bilthoven, resulting in two complete series of the monthly amounts of rainfall and the tritium levels in the water. Moreover, RIVM and the Royal Netherlands Meteorological Institute (KNMI) started a cooperation in 1980 to sample the precipitation at 13 meteorological stations (*Table 4.2* and *Fig.4.3*), aiming at an investigation of the chemical composition of precipitation. Within the programme, samples were also taken for an analysis by CIO of their tritium levels. After 1988, the sampling programme for tritium determinations was reduced to four stations. Hence, for the period 1980-1988, monthly series of the tritium level in rainfall are available for 13 stations, evenly distributed over the country. The series was used for an elaboration of tritium levels in precipitation within the framework of groundwater recharge studies. Yearly averages were determined by calculating rainfall weighted means.

Groundwater samples were taken using different techniques. For special investigations, so-called 'mini-screens' (finger-sized) were attached to the central rising pipe of a borehole, at intervals of half a metre. In later years, the mini-screens were replaced by small screens of one inch in diameter and a length of one decimeter, usually at intervals of one metre. In standard monitoring practices, the wells of the Groundwater Monitoring Network (LMG) were drilled by cable-tool drilling; the wells were provided with observation screens 2 metres long. The mini-screens, the small screens and the LMG screens were pumped by suction and sampled by applying the normal RIVM procedures for the sampling of wells. Samples were taken in polyethylene bottles and sent to the laboratories of either CIO or RIVM for the determination of tritium levels. In both cases, the liquid scintillation counting technique was used after enrichment of the samples. Enrichment is necessary because of the relatively low levels of the expected values. The Provisional NEN 6420 was followed, as well as Florkowsky (1981), and Sauzay and Schnell (1972).

Tritium levels are expressed in Tritium Units (TU) in which 1 TU represents a radiation of 0.12 $Bq \cdot l^{-1}$. In comparing two series of data, the same reference date should be used in order to account for radioactive decay of the tritium atoms.

4.2. A reference series of tritium levels in precipitation

The analysis of the two series of monthly determinations in Groningen and Bilthoven resulted in values of average yearly tritium levels in rainfall and the expected seasonal fluctuations. With regard to groundwater studies, more detailed knowledge is not necessary for two reasons:

1. During subsurface flow, beginning already in the unsaturated zone, a natural mixing (dispersion) will occur, such that groundwater in the saturated zone is mixed, probably at least on a yearly basis (section 2.2.1).
2. Sampling is done by pumping. Certainly in longer screens, but even at pumping a mini-screen, mixing will occur.

In some practical situations, an even stronger mixing in groundwater has to be assumed, which can be represented by moving averages over longer periods than one year. Nevertheless, seasonal fluctuations are important in cases where a non-uniform contribution of the yearly rainfall to groundwater recharge is occurring.

Values in the 1960-1970 period can be based on measurements in the Vienna region by establishing a relation with the Groningen measurements and by taking into account the change in the pattern of tritium levels in European rainfall after 1970 (Weiss et al.,1978), mainly because of local emissions from nuclear industries. From correlations relating monthly values from Vienna and Groningen (GR) measured in the period after 1970, it appeared that the observed values obeyed the equation: GR = 0.7*VIENNA.

However, according to Weiss et al. (1978), the relation between values observed at Vienna and in the Netherlands changed around 1970. The relation during the period 1960-1970 (Fontes, 1985) was:

GR = 0.6*VIENNA

The latter relation has been used to estimate the yearly averages of tritium levels in Groningen rainfall during the period 1960-1970. For the period before 1960, use had to be made of observations at Ottawa (Stuijfzand, 1986) and resulting in estimates for yearly averages in Groningen rainfall in the period 1950-1960. A reference series for average annual tritium levels in Groningen rainfall has been based as follows: for 1950-1960 on Ottawa data, for 1960-1970 on Vienna data; after 1970 on local measurements. Levels of less than 5 TU are assumed to have occurred in the period before 1950. Hence, a complete series is available, represented in *Table 4.1* and in *Fig.4.1*, where two different reference dates are used. Values for any other date follow from the relation representing radioactive decay:

$$A_t = A_0 * e^{-0.05576*t}$$

where: A_t and A_0 represent levels (TU) at times t and 0 (years).

The available data were analyzed with a Fast Fourier Transformation, supported by autocorrelograms. Elaboration by Van der Valk (1987) of the monthly values determined in the period 1980-1986 at first implied the elimination of the long-term trend.

The long-term trend in the Groningen monthly observations obeyed the equation:

Table 4.1. Rainfall weighted means (TU) of tritium levels in Groningen precipitation per 1991-01-01 (data CIO)

1991	17	1977	28	1963	413
1990	12	1976	25	1962	114
1989	13	1975	47	1961	11
1988	14	1974	36	1960	18
1987	14	1973	34	1959	56
1986	18	1972	32	1958	42
1985	14	1971	51	1957	8
1984	14	1970	38	1956	9
1983	14	1969	41	1955	3
1982	13	1968	41	1954	19
1981	17	1967	49	1953	1
1980	17	1966	86	1952	1
1979	22	1965	129	1951	1
1978	35	1964	245	1950	1

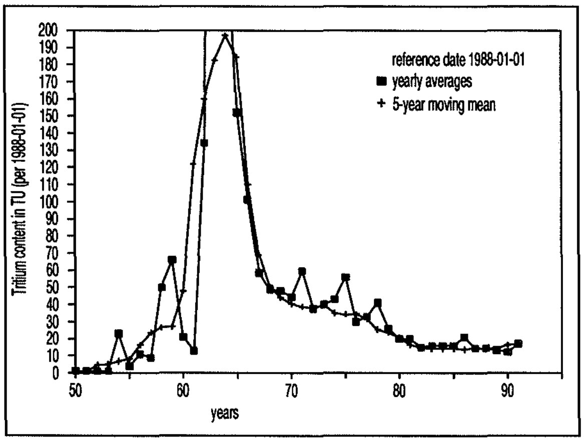


Fig.4.1 Tritium levels in Groningen rainfall.

$$A_t = A_0 * e^{-c*t},$$

where: A_t and A_0 are levels (TU) at times t and 0 (months).
c = a constant (month^{-1})

Elaboration resulted in a value of c=0.0142 month^{-1} for the Groningen data, corresponding to a decay rate at a half-life of 49 months, implying that, apart from radioactive decay, other tritium sinks also play a role. A series of trendless values e_{res} was obtained by dividing the measured values by the corresponding values computed from the trend. The next step was to apply Fast Fourier Analysis to the e_{res} values, yielding a number of cosinusoidal components of the total curve of e_{res} values with time. The contributing cosine, which was the most important, appeared to have a period of 12 months. Hence, a seasonal effect became apparent, implying maximum values in July and minimum values in January (see also *Fig.4.2*, where values of (e_{res}-1) have been represented and a corresponding cosine graph has been added). To estimate the significance of the seasonal effects, the relationships between the yearly levels, and between the total summer levels and the total winter levels, were determined by linear correlation. No clear correlation resulted, but roughly the following relationships were obtained:

A(winter) = 0.75 * A(year);
A(summer) = 1.25 * A(year).

If groundwater recharge occurs during short periods of a few months, factors even smaller and larger will apply in winter and in summer periods, respectively.

Regional variations were established by correlating the other series of data with the Groningen data in two ways:

a. All monthly values of the respective stations were linearly correlated with the corresponding Groningen values, resulting in factors indicating

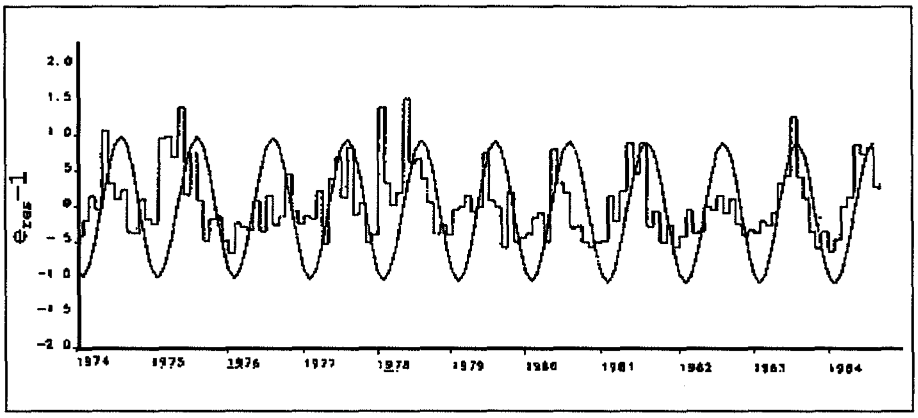


Fig.4.2. Monthly fluctuations and seasonal trends in the tritium levels of precipitation.

the relationship between values for the various stations and those for Groningen.

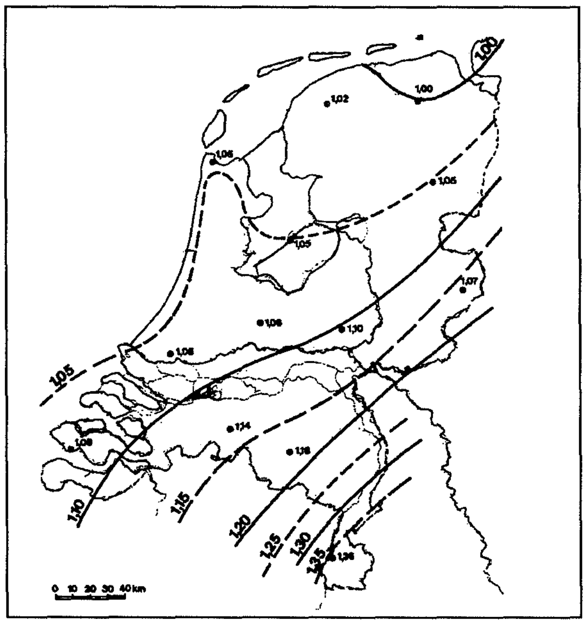
b. The total tritium volume over the full period was determined for each station by accumulating the products of monthly rainfall and respective tritium level. The ratio between the total volume for a given station and that for Groningen indicates a possible relation.

Both methods yielded slightly deviating results. In the first instance, the averages of the two factors (*Table 4.2*) for each station were taken. The values of *Table 4.2* were also used to compose *Fig.4.3*, indicating the regional trend across the Netherlands. A relatively strong gradient exists, with the lowest values near the coast. Although the given relations were only established for the period from 1980 to 1986, they were extrapolated to the past, assuming that the resulting values are accurate enough to allow a comparison with groundwater tritium data. As a result, tritium levels may be estimated in the precipitation of the Netherlands for any place and at any time. The interpretation of groundwater data, as outlined in the following chapters, resulted in a further calibration.

Table 4.2. Correlations between the tritium levels in the rainfall of meteorological stations.

station	correlation	tritium volume	average
Groningen	1.00 (ref.)	1.00 (ref.)	1.00
Leeuwarden	1.03	1.01	1.02
De Kooij	1.01	1.09	1.05
Witteveen	1.08	1.02	1.05
Lelystad Haven	1.04	1.06	1.05
Vliegveld Twente	1.16	1.18	1.17
Zestienhoven	1.02	1.07	1.05
De Bilt	1.05	1.06	1.06
Deelen	1.11	1.08	1.10
Vlissingen	1.04	1.11	1.08
Gilze Rijen	1.13	1.15	1.14
Eindhoven	1.16	1.19	1.18
Beek	1.33	1.39	1.36

Fig.4.3. Regional trends in the yearly averages of the tritium levels of precipitation.



4.3. Interpretation techniques for groundwater tritium

4.3.1. Various hydrological situations

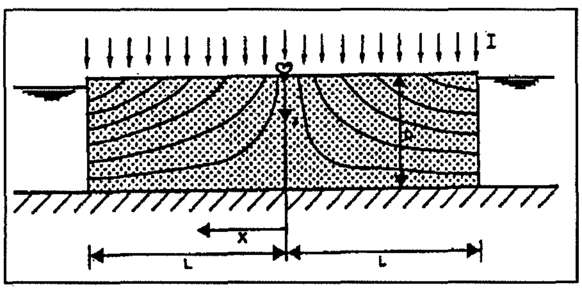
During investigations, the tritium levels in groundwater are normally measured in samples from screens at given depths in wells at given locations. The observed tritium levels have to be compared with the levels in local rainfall, which, in general, is the origin of the groundwater recharge in the sandy regions of the Netherlands. The interpretation has to take into account that the hydrological situation may be complicated, involving specific conditions governing the downward flow. Some cases to be distinguished are:

A. Constant recharge of a single and homogeneous aquifer

When comparing tritium levels in rainfall and in groundwater, the possible groundwater flow patterns have to be taken into consideration. The equation governing the flow should be known beforehand. The interpretation results in the determination of the parameters values being valid for the investigated location. The most simple situations concern flow in a single and homogeneous aquifer. The first approximation is to assume a constant vertical velocity of the downward groundwater flow. In this case, the downward percolation is linear with time and the interpretation can simply be based on a comparison of both profiles, resulting in the rate of (actual) groundwater flow. However, in nature the vertical groundwater flow is neither constant in time, nor constant in depth.

Fluctuations in time of the vertical groundwater flow will be caused by variations in groundwater recharge, resulting from changing meteorological conditions. Annual variations in recharge will lead to a varying vertical flow. However, the resulting tritium levels in saturated groundwater will correspond to the levels belonging to an average situation. Hence, the assumption of a constant recharge of the saturated

Fig.4.4. Flow scheme for the flow in a single aquifer.



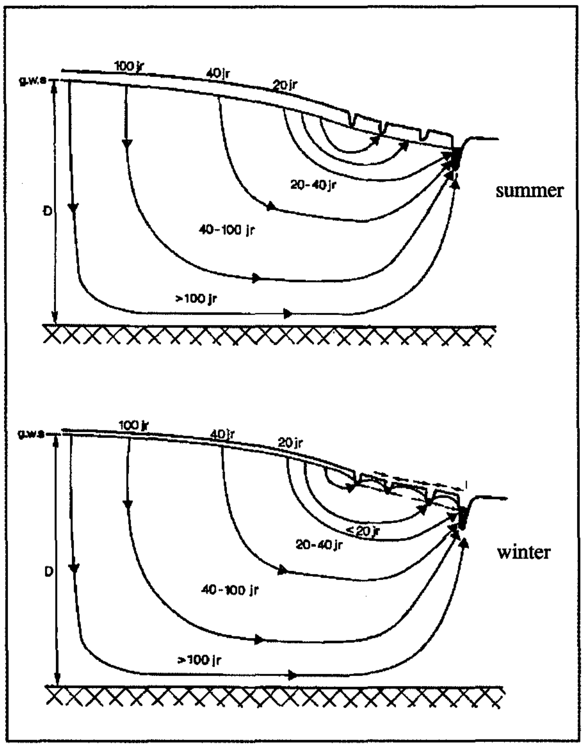


Fig.4.5. Various components of rainfall runoff and groundwater discharge.

groundwater will result in a determination of the long-term average of the downward velocity.

In general, the downward vertical flow rate will be maximum at the top of single aquifers, recharged by a constant rainfall. At increasing depths, the vertical velocity will decrease, but the horizontal flow will remain relatively constant. In the practical case of regional groundwater flow, which is recharged by a constant precipitation (*Fig.4.4*), the equations developed by Bruggeman and discussed in section 2.2.2 may be used. The regional flow equations, as shown below, are valid at distances from the draining open water, which should be larger than the aquifer thickness:

$$t = pD/I*\ln(D/(D-z)); \text{ and}$$
$$z = D*(1-\exp(-It/pD));$$

where: t = travel time (years);
z = depth below top of the aquifer (m);
p = porosity (dimensionless);
D = thickness of the aquifer (m);
I = groundwater recharge ($m \cdot a^{-1}$).

B. Spatial variations in a single aquifer

A more realistic representation of an actual flow situation is given in *Fig.4.5*, showing that in stream zones, where the groundwater flow is discharged, deviations from the schematical flow of *Fig.4.4* may occur. A main deviation is that the groundwater recharge is also influenced by surficial discharge components and, moreover, that the incomplete incision of the stream will lead to a more complicated flow pattern. For such situations, use can be made of numerical simulations, for example, as proposed by Veling (1992).

In the great majority of relatively high areas, the rainfall is fully discharged by actual evapotranspiration and by groundwater flow. Normal evapotranspiration, largely consisting of plant transpiration, will virtually not change the original isotope levels of infiltrating rainfall (Mook,1989). In forest areas (*Fig.4.5*), open water evaporation of rainfall intercepted by the tree canopy can be part of the evapotranspiration. Surficial discharge components (overland flow and interflow) may, in other areas, remove part of the rainfall, thus limiting the groundwater recharge. A partial discharge by open water evaporation, or by surface runoff, may entail seasonal effects in the groundwater isotope levels. The interpretation of such effects in observed groundwater data, will also yield information with regard to the hydrological situation.

C. Shallow groundwater in seepage areas
In areas where groundwater is discharged by upward vertical flow to a seepage zone (*Fig.4.5*), the interpretation of groundwater tritium levels may encounter problems. The deep groundwater has resided mostly in the subsurface for a period greater than the age for which a tritium dating is possible (after 1950). However, the shallow subsurface in seepage areas still may transport groundwater recently recharged. A transition zone between older and more recent groundwater will exist at a depth which is previously unknown.

D. Groundwater flow in multi-layered aquifers
The Netherlands soil, deposited under natural conditions, contains a large variety of components. Not only clayey and peaty layers may intercalate with sandy layers, but also the grain sizes and the silt level may differ within a sand layer, implying heterogeneous permeability conditions. Variable flow conditions will prevail, instead of a homogeneous flow. Two situations will often occur:
1. A predominantly homogeneous aquifer is covered by a less permeable layer. The horizontal transport in the covering layer will be small, but flow in the vertical direction is possible. In such cases, it is not the full amount of precipitation minus the actual evapotranspiration that will percolate. Because surficial flow components will discharge part of the water, an interpretation has to be based on a smaller downward flow, starting at the top of the homogeneous aquifer.
2. A less permeable layer divides a sandy layer in two sub-aquifers. The interpretation has to be split in two parts. The tritium levels in the upper layer should match the vertical percolation to the upper layer; the levels in the lower layer have to match the vertical flow in that layer.

4.3.2. Various tritium data sets

4.3.2.1. Tritium profiles in single wells

A tritium profile is available if groundwater levels were measured in samples collected on the same date in a range of screens in one well. The hydrological situation in the period preceding sampling is roughly the same for all samples. But possible errors in individual measurements also become less important. Rainfall levels at the location in the years before recharge can be estimated. The interpretation is based on a comparison of rainfall and groundwater tritium levels, according to the following procedure:

1. One fixed reference date is chosen. The sampling date is usually chosen as the reference date, but another fixed date may also be taken. All tritium levels from both series of observations (groundwater and rainfall) are recalculated, using the chosen reference date.
2. Groundwater tritium levels are represented in a graph.
3. The factor, f, indicating the regional effect in rainfall levels is taken to be equal to the value derived from *Fig.4.3*. The local rainfall data is introduced in a graph representing an assumed groundwater recharge with $I/p=1\ m{\cdot}a^{-1}$ (first approach) at the well location. The downward percolation obeys the regional flow equation, where the value of D is already known from general geological information.
4. The two profiles are matched and calibrated by varying the values of f and I/p. The best match determines values for f and I/p. Note that f is also a variable to be optimized. The factor f represents a regional effect in rain (*Fig.4.3*), but it may also represent a possible change, for example, by enrichment. The variation in f results in a vertical displacement of the curve, but also in a slight deformation.

Three examples can elucidate the interpretation of tritium profiles, which are represented in the 1983 observations at the Venhorst farmland, the 1984 observations at Rips forest and the 1981 data from the Leiden sportfields. The Rips and Venhorst locations are close to each other. Hence, it may be expected that the rainfall tritium levels are virtually the same,

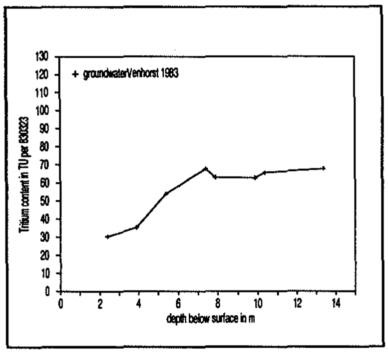


Fig. 4.6. Groundwater

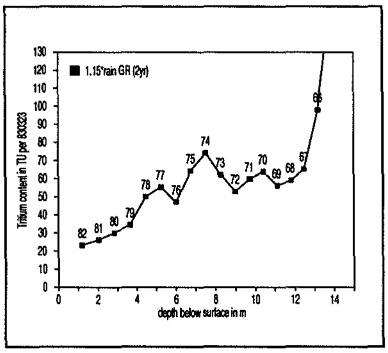


Fig. 4.7. Rainfall

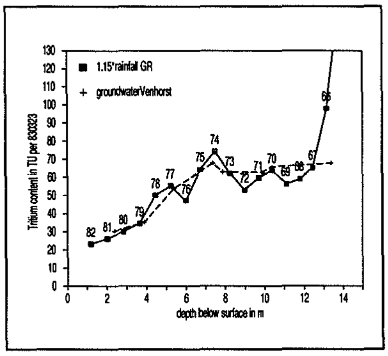


Fig. 4.8. Matching

Fig. 4.6, 4.7, 4.8. Interpretation of the tritium contents of groundwater, sampled at Venhorst in 1983.

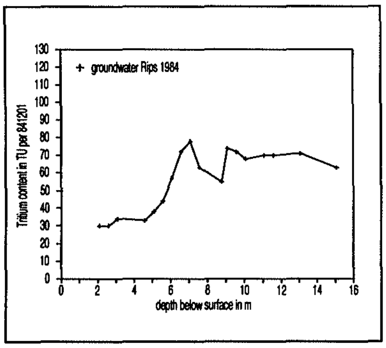


Fig. 4.9 Groundwater

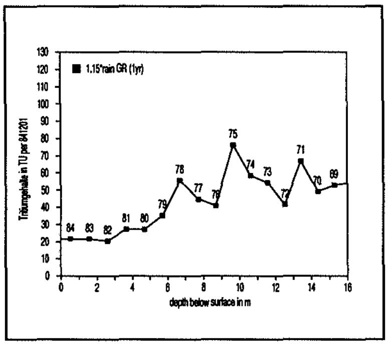


Fig. 4.10. Rainfall

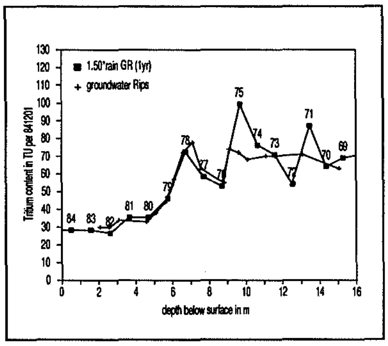


Fig. 4.11. Matching

Fig. 4.9, 4.10, 4.11. Interpretation of the tritium contents of groundwater, sampled at Rips in 1984.

even when the Rips observations were taken one year later. Yet, marked differences were noted in the groundwater tritium levels, which lead to the interpretation (see *Fig.4.6 to Fig. 4.11*):

Venhorst:	f=1.15;	I/p=0.83 m·a^{-1};	2-year moving mean;
Rips:	f=1.50;	I/p=1.07 m·a^{-1};	1-year moving mean;

The results concerning the downward percolation, I/p, are in the range of expected values, as will be discussed later. In the Venhorst groundwater, the factor f=1.15 corresponds to the regional effect in rain, as previously determined, but a larger factor, f=1.50, is determined in Rips groundwater. A possible explanation is that open water evaporation from intercepted rain affecting the groundwater in Rips forest also causes an enrichment of the tritium levels, leading to a larger multiplication factor, f.

Two profiles are available from samples taken at the same date at a sportfield compound in the city of Leiden. The samples were analyzed by two different laboratories (CIO and RIVM). The comparison of the results is important for the sake of consistency between series analyzed by CIO and other series analyzed by RIVM, if the interpretations of both types of data are to be compared. Specific results at the Leiden location are:

Leiden: f=1.60; I/p=1.31 m·a^{-1}; 1-year moving mean;

The relatively high value of I/p=1.31 m·a^{-1} may be explained by the sprinkling of the sportfields in summer periods. A value of f=1.6 is larger than the regional factor in rain (f=1.05). The high value probably indicates the influence of seasonal effects related to an excess of sprinkling water in the summer months (effects of open water evaporation) and drainage in the winter periods. The matching is not perfect, reflecting practical situations in which a perfect fit is never reached. Another conclusion is that the results of tritium analyses by the RIVM and CIO laboratories are consistent.

4.3.2.2. Interpretation of LMG and PMG data

Between 1983 and 1984, the screens of the LMG wells of the National Groundwater Monitoring Network were sampled and the tritium levels analyzed by CIO. Samples withdrawn in 1991 from the screens of the later installed PMG wells of the pro-

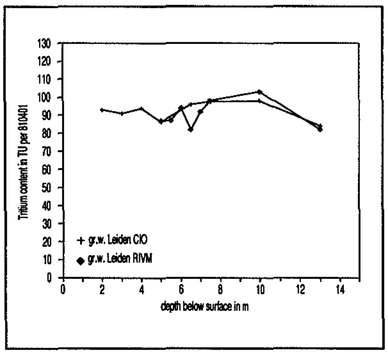


Fig. 4.12 Groundwater

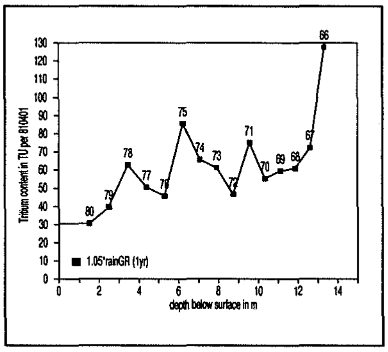


Fig. 4.13. Rainfall

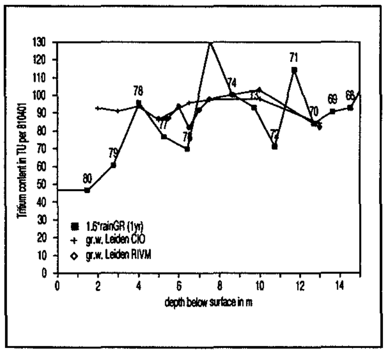


Fig. 4.14. Matching

Fig. 4.12, 4.13, 4.14. Interpretation of the tritium contents of groundwater, sampled at Leiden in 1981.

vincial network in Gelderland, were also analyzed by CIO. All LMG wells in the Netherlands have a similar construction. Screens were installed at depths of 8-10 m, of 13-15 m and of 23-25 m. At locations where clay or loam layers prevented installation, the screen depths were adjusted, but not more than necessary. For part of the wells, the deepest screens were sampled in 1982 to determine the tritium levels. A second round followed in 1983, or 1984, sampling the most shallow and the deepest screen of all the wells. Two or three observations of the tritium level are available for many wells. The PMG wells have a similar set-up, but the most shallow screen has been placed at a depth of about 5 m below land surface. The PMG wells were sampled during autumn 1990. Mostly, three observations per well are available.

For the interpretation, five-year moving means of tritium levels in rainfall are used; these have the advantage of rising continuously in the period 1950-1963 and falling continuously in the period 1963 to date. Imaginary profiles (using the factor f valid for rain in the area concerned and a first estimate of $I/p=1$ m·a^{-1}), valid on the sampling dates, are represented in Figs.4.15 and 4.16. Not all of the wells yielded suitable tritium data. In some cases, old water was sampled, showing no measurable tritium levels; in other cases, the data fell for unknown reasons below the expected range. Only wells in sandy regions are interpreted. Where an interpretation was possible, the procedure was:

1 Fixed reference dates were chosen in order to enable the comparison between rainfall and groundwater data; the reference date corresponded to the time of sampling. The tritium data were recalculated, based on that date.
2 Tritium values for the upper screen of the LMG wells were compared to the rising line of *Fig.4.15* and the value for the deepest screen with the falling line. For PMG wells a similar procedure was followed, using the falling line of *Fig.4.16* for the

Fig.4.15. Infiltrating rainfall per 1984-06 for D=40 m; I/p=1 m·a^{-1}; f=1.15; 1982 and 1984 observations.

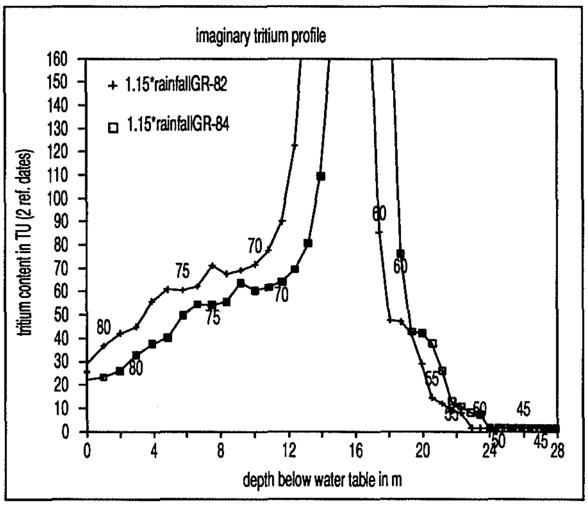
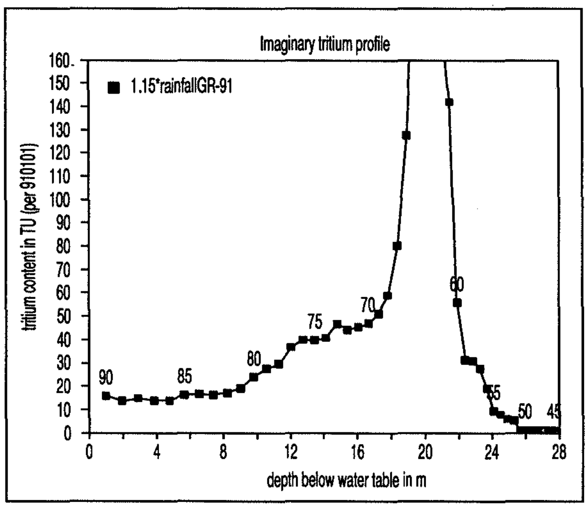


Fig. 4.16. Infiltrating rainfall per 1990-10 for D=40 m; I/p=1 m/yr; f=1.15; 1990 observations



two upper screens. The year of recharge can be estimated for each observation.

3 It was assumed that at the prevailing groundwater levels, the average residence time of water in the unsaturated zone would be one year. The level of the phreatic water table was known for each well; deep levels necessitate an adaptation of the unsaturated travel time. Travel times in saturated groundwater were calculated by subtracting the year of recharge from the sampling date.

4 In the flow equation for saturated flow, valid in the regions considered (where D is known), the time t and the depth z can be established after the foregoing steps. Values for I/p can be derived and also values for I, if a value for the porosity is assumed (p=0.35 is taken).

5 The results for one well were compared and if in agreement, the values were averaged. Unlikely values were omitted. In that case, only the more probable values, derived from the other observations were taken.

LMG well no.1 in East-Gelderland (D=40 m) can be used to demonstrate the interpretation of the data.

<u>Screen 1</u>; depth of 9-11 m, (^{3}H)=56 TU was measured in 1984; recharge in 1974; travel time t=9 years; Result: I/p=0.72 m·a^{-1}.

<u>Screen 3</u>; depth of 23-25 m, (^{3}H)=26 TU was measured in 1984; recharge in 1956; travel time t=27 years; Result: I/p=0.95 m·a^{-1}.

<u>Screen 3</u>; depth of 23-25 m, (^{3}H)=7 TU was measured in 1982; recharge in 1953; travel time t=28 years; Result: I/p=0.92 m·a^{-1}.

The average value is I/p=0.86 m·a^{-1}, resulting in I=301 mm·a^{-1}.

4.3.2.3. Tritium data from surface water

The tritium levels in surface water represent a situation in which the inflow of water has various ages. With regard to groundwater flow, the tritium level of recharge has changed in the last 40 years from water virtually without tritium, to rainwater with a certain level. The surface water receives older groundwater without tritium, but also younger water with tritium amounts, constituting a representation of the rainfall tritium levels over the years after 1950.

For the flow of groundwater towards the draining surface water (*Fig.4.17*), an equation (Thunnissen, 1987) can be elaborated with regard to average tritium levels of incoming water, if the recharge changes stepwise from water without tritium to water having the average content in rainfall after 1950. The tritium level of surface water can be derived from the adapted equation, where c_0=0 in the period before 1950:

$$c_{out}=c_{in}*(1-\exp(-It/pD)),$$

where: c_{out} and c_{in} represent values, observed, respectively, in the surface water and estimated in the recharging groundwater in the years after 1950; t=sampling date-1950 (years); D=aquifer thickness (m); p=porosity; I=recharge rate (m·a^{-1}), which is to be determined. An elaboration in section.6.4. concerns the tritium levels in the Veluwe sprengen.

4.4 Discussion and conclusions

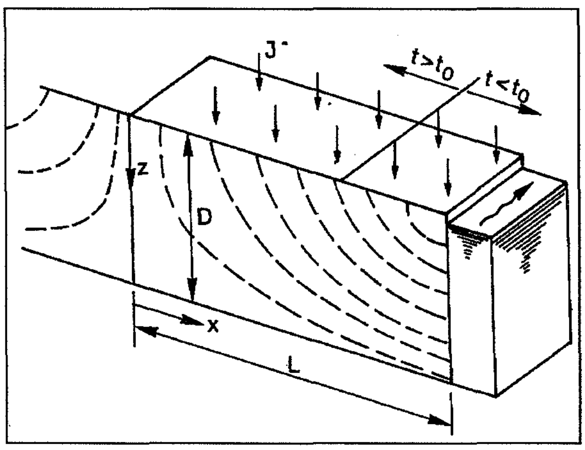
The measured tritium levels in rainfall of the Netherlands regions have been elaborated in a form which is suitable for groundwater studies, resulting in the conclusion that:

A reference series of tritium levels in rainfall is available for use in groundwater studies, allowing an estimate of the levels in precipitation at any time in the past and at any place in the Netherlands.

The analysis of rainfall tritium levels in the period 1980-1986 resulted in a determination of regional factors indicating the differences between precipitation in Groningen and precipitation in twelve other meteorological stations. The conclusion is:

A relatively strong regional gradient in the tritium levels of precipitation has existed in the Netherlands since 1970. The lowest values occur near the coast and the levels increase land inward.

Fig.4.17. Groundwater flow to surface water.



The hydrological situation of the groundwater in the sandy regions of the Netherlands varies. An important difference is the occurrence of recharge areas and seepage zones, which, evidently, will have a strong effect on the resulting tritium levels in the groundwater. Other differences are related to special components of rainfall discharge, such as surficial runoff or open water evaporation. The analysis of tritium levels in groundwater should take into consideration possible seasonal effects. The interpretation may indicate such effects, leading to the conclusion:

If resulting in a determination of seasonal effects, the analysis of groundwater tritium levels, may give indications as to the hydrological situation.

The availability of tritium profiles provides good conditions for an interpretation of groundwater data in the case of recharge by precipitation. Groundwater data can be interpreted by matching rainfall and groundwater tritium data. In practical situations a perfect fit is almost never reached. Derived from the comparison of two data sets is the conclusion that:

The results of the RIVM and CIO laboratories for the analysis of tritium levels are compatible.

For the LMG and the PMG wells, only 2 or 3 observations are available per well, implying the use of appropriate techniques for the interpretation of tritium levels. A method to interpret the relatively few observations from individual monitoring wells is proposed. The result may be erroneous, given the possible sources of errors in the determination and interpretation of tritium in groundwater. Therefore, it can be stated that:

Individual measurements of the tritium level can lead to misinterpretations; a tritium profile in one well or a number of related observations is preferred.

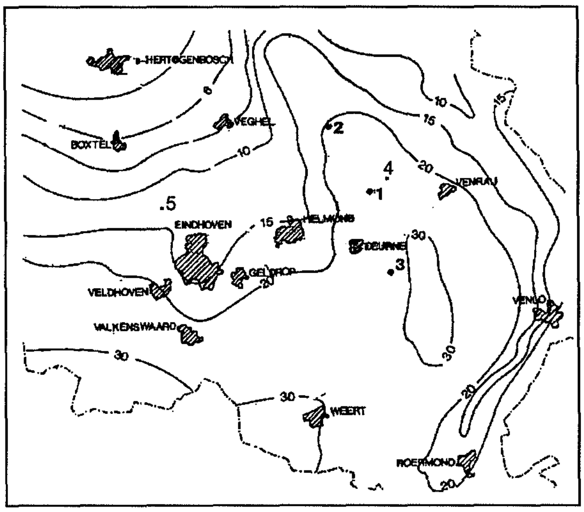
5. FIVE ILLUSTRATIVE CASES

5.1. Features of the detailed studies

The methods used to estimate travel times and the recharge of shallow groundwater can be illustrated by considering the results of five detailed geohydrological investigations in the east part of the province of North Brabant. In *Fig.5.1*, their situation is indicated, with the locations Stippelberg (1), Venhorst (2), Griendtsveen (3), Vredepeel (4) and Best (5). The five cases investigated showed the following interesting features:

a. The fieldwork consisted of a detailed reconnaissance of the local hydrological situation, including the determination of tritium profiles for the same well in two different years. The first series was determined by CIO and the later analyses done by RIVM. The comparison of results not only indicates possible changes in the vertical groundwater velocity over the years investigated, but also provides an opportunity to evaluate the consistency of both analyses.
b. The available data often allowed estimation of groundwater travel times in more than one way. The results could be compared and, in this way, mutually validated.
c. The investigated hydrological situations showed a large variety. The Venhorst farmland is used for intensive husbandry. Stippelberg forest has many open spaces; the well where the tritium profiles were determined is even situated at the fringe of an open space. The well at Vredepeel forest is situated near a lane in a forest, which was cleared between both sampling dates, resulting in a change of flow patterns. The sampled well at the border of the Griendtsveen nature reserve receives groundwater, recharged in a raised bog and in an adjacent swamp, where peat growth is stimulated again. A shallow loam layer of a great areal extent is present in the shallow soil of the Best test location, causing a surficial discharge of part of the rainfall excess.

Fig.5.1. Location of the investigated sites; isohypses



Four locations are situated in the Peel region, where the shallow aquifer system forms the upper zone of a structurally elevated geological unit, called the Peel horst. Groundwater flows in a shallow aquifer from the central water divide towards the east and west edges of the area (*Fig..5.1*). The Best location is found in the valley of the Central Graben, which is a structurally subsiding geological unit adjacent to the Peelhorst. The subsurface contains sandy sediments to a depth of several hundreds of metres, which are subdivided in separate sub-aquifers by intercalated clay layers. The upper aquifer is covered by less pervious deposits, at the Best location to a depth of 25 m below surface. A variable part of the rainfall excess at Best recharges the groundwater flow in the upper aquifer. The flow in this aquifer is to the northwest (*Fig.5.1*) and it is discharged by local streams

5.2. The Stippelberg forest at Rips

5.2.1. Situation and investigations

The investigated location at Rips is situated in a drier part of the former wastelands of the Peel area. Shifting sands occurred at Stippelberg, where windblown dunes were still active in the year 1850. Around 1900 the shifting sand was immobilized by the planting of pine trees. Remnants of former inland dunes can still be recognized (*Fig.5.2*). The present Stippelberg forest has a mixed character through the natural growth of deciduous trees (*Fig.5.4*); the forest has become a nature reserve, occupying an area of some 10 km^2. Due to poor soils, the tree vegetation is not dense. The site of investigation is an open space in the centre of the forest, presumably a former blown out valley with shallow groundwater levels. The rest of the forest has also many open spaces. The vegetation in the open field consists of heather and grasses, and

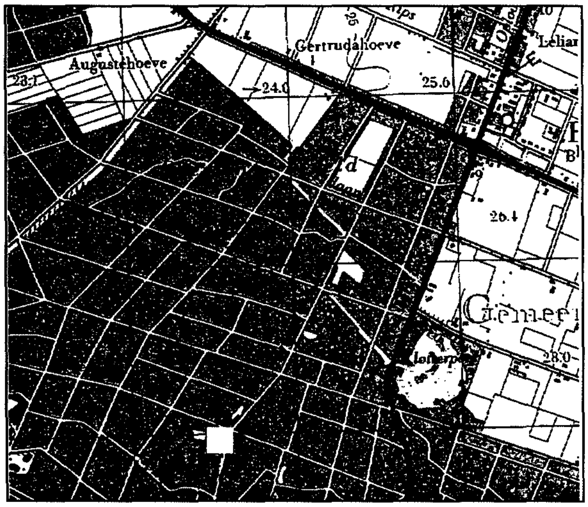


Fig.5.2. Situation of the Stippelberg forest.

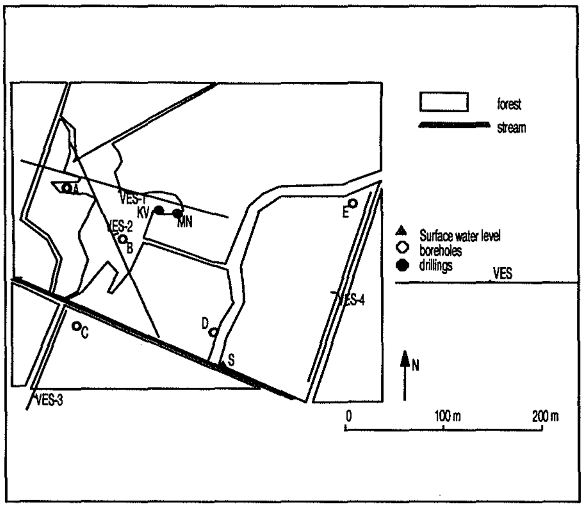


Fig.5.3. The investigations near the KV well.

even a small pond , nowadays protected by a concrete lining. Land surface at the open space is roughly 25 m above mean sea level, the low hills are a few metres higher. The water course De Snelle Loop was dug in Stippelberg forest mainly to drain the eastern part. When surveyed, the level of the open water was above groundwater level. Groundwater drainage at the site is by subsurface flow.

Since 1980, the area has been under investigation. In the open space (*Fig.5.3*), a cable-tool drilling (KV) was installed near an observation well (MN), of the national groundwater monitoring network. Mini-screens were installed in the KV well, at intervals of 0.5 m, from the groundwater table to a depth of 14 m. In 1981, the KV well was sampled in all four seasons to investigate the chemical composition. Also, for one of the sampling dates, the ^{18}O and tritium levels were determined by CIO. Additional investigations took place at the end of 1984 and on 1985-02-05; these involved the installation of five temporary boreholes, carrying out four geo-electrical measurements (VES) and the realisation of an EM-31 survey, covering the surroundings of the wells. The four VES were located in a way that two VES were situated in the open space and two other VES in wooded areas, because it was

Fig.5.4 . The open space in Stippelberg forest.

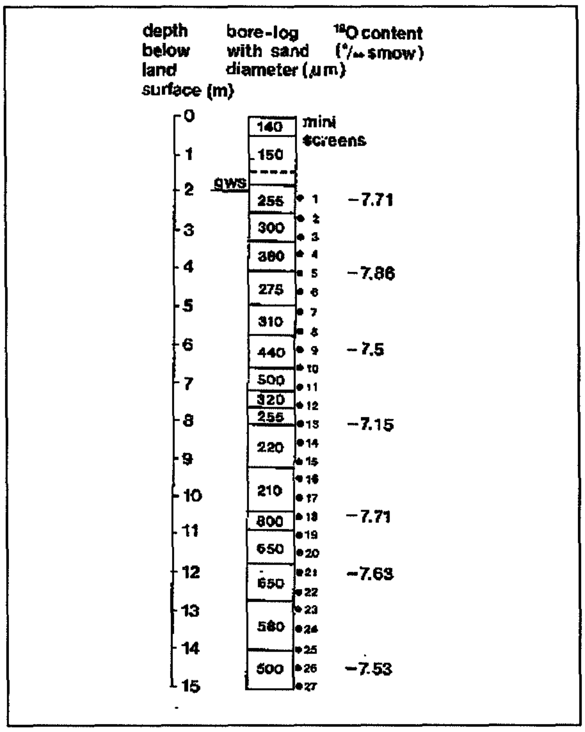


Fig.5.5. The KV well data.

expected that the shallow groundwater quality would differ in both cases. The distances between the spreads are small, and no significant changes in the geological structure of the subsurface are likely to occur. The resistivities of deeper layers should be roughly the same. Sandy layers of a certain thickness will have the same resistivity, but the thin loamy or clayey layers may vary in thickness. To draw groundwater isohypses, the groundwater levels in the various wells were measured and the well heads surveyed. All observation wells were sampled and the water analyzed with regard to chemical properties. The observation screens of the KV well were sampled again for determinination of the tritium content of the water at the RIVM laboratory.

5.2.2. Soil structure and geophysical surveys

The old sand dunes contain relatively fine sand; however, the Veghel Formation, with layers of coarse sand, is already present at shallow depths. In *Fig.5.5*, the grain sizes of soil samples from the KV well are presented and also the observed ^{18}O levels. The VES interpretation is shown in *Figs.5.6* to *5.9*. The older sandy formations underneath the KV well are developed to a depth of roughly 100 m, where Tertiary clay layers form the base. The measurements in the open space and under trees show marked differences. The unsaturated zone has a higher resistivity in the open space, where a shallow saturated layer with a relatively high resistivity is present; this is lacking underneath trees. The high resistivity layers represent the groundwater recharge, having a low conductivity, in the open space. The conductivities of the water samples from boreholes in the open space were roughly 6 $mS \cdot m^{-1}$, resulting in a formation factor of approximately F=5.

The layers down to a depth of 25 m have a resistivity of about 250 Ωm and groundwater in this layer has conductivities between 18 and 22 $mS \cdot m^{-1}$ (Duijvenbooden, 1985), also resulting in a formation factor of F=5. Hence, the shallow sandy layers have similiar features everywhere and differences in resistivity will largely be caused by differences in the conductivity of the groundwater. In between 25 and 30 m, 3 out of the 4 VES carried out, indicate loam layers, probably belonging to the Tegelen Formation. The resistivity of the deepest layer is in all cases 600 Ωm. The measurements do not allow accurate determinination of the base of the layer at a depth of roughly 100 m, which has a relatively low resistivity. Below that depth, clay and loam layers with a low resistivity are present.

Assuming that the formation factor of the deep layer, with a resistivity of 600 Ωm has a maximum value of F=5, the conductivity of the groundwater is maximum 8 $mS \cdot m^{-1}$, implying that groundwater has about the same conductivity as shallow groundwater in the open space. The conclusion is that the groundwater in layer 5 has been recharged before the existence of the forest, in the time before 1900, when inland dunes were present in the area. The subsurface up to a depth of 100 m most probably acts as one single aquifer.

The values measured with the EM-31 are indicated in *Fig.5.10*, showing the effect of the open space. The values, measured with the EM-31 in wooded areas, usually vary between 2.0 and 2.5 $mS \cdot m^{-1}$. In the open space, the EM-31 values range from 1.0 to 1.5 $mS \cdot m^{-1}$. The low values are most likely caused by the effect of a relatively small conductivity of the upper groundwater, as already observed in the VES. Values decrease in a downstream direction because of an increasing zone of low conductivity. An interesting feature is the occurrence of slightly elevated EM-31 values, between 2.5 and 3.0 $mS \cdot m^{-1}$, to be found in particular on the windward side of the wooded area. The higher conductivity probably corresponds to an increased flow of chemical compounds into the soil caused by the catchment of aerosols by the forest edge.

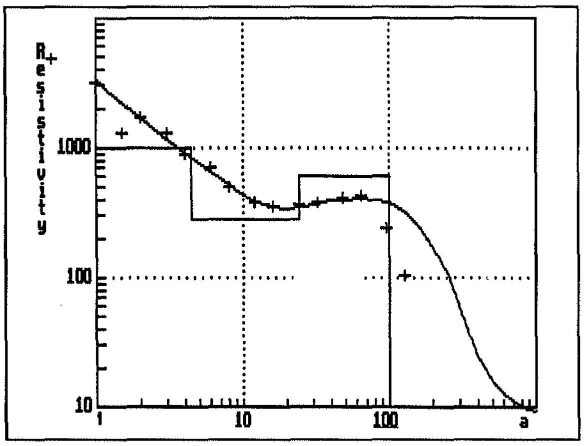


Fig.5.6. VES Rips-1.

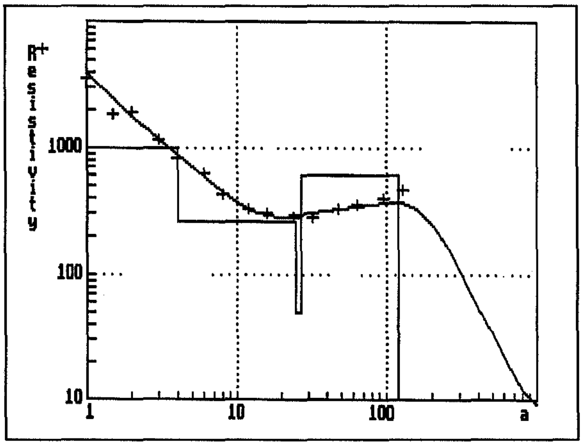


Fig.5.7. VES Rips-2.

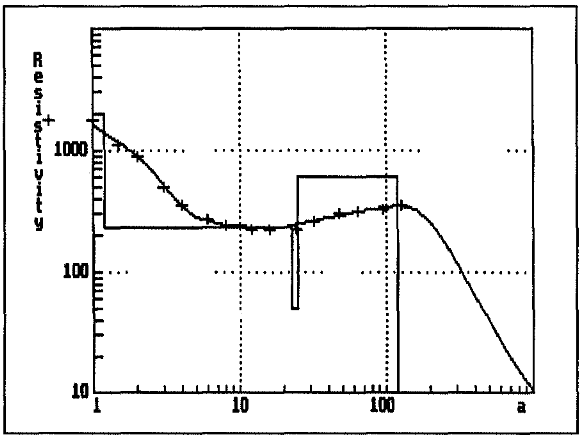


Fig.5.8. VES Rips-3.

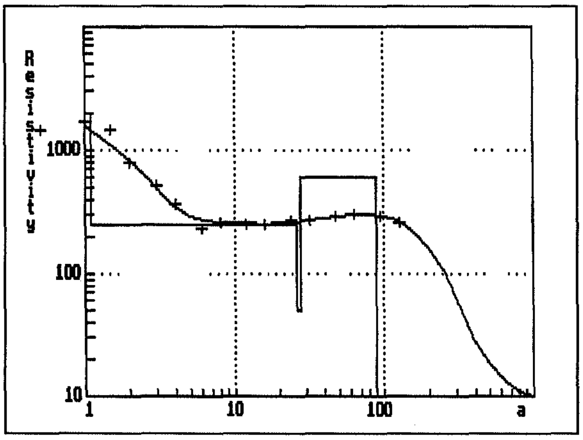


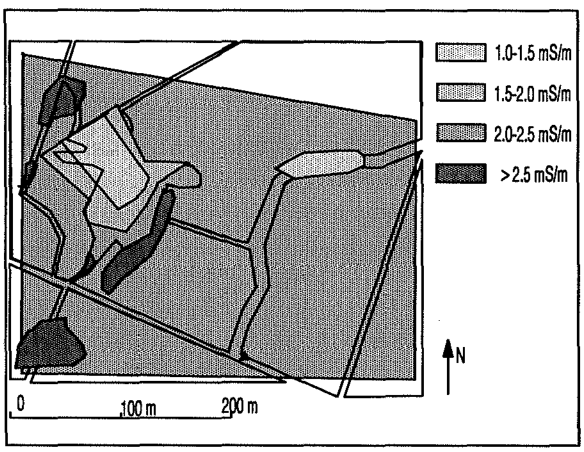
Fig.5.9. VES Rips-4.

5.2.3 Isohypses and tritium data

The groundwater heads at 1984-12-03 were at levels of 1.19m (borehole A); 0.53m (B); 0.68m (C); 0.71m (D) and 0.82m (E) below land surface. A map of the composed groundwater contours is shown in *Fig.5.11*. It follows that the direction of the flow is roughly from east to west, which agrees with the regional trend (DGV-TNO, 1976). The gradient in head is about 1:600. No marked influence of the open water course on groundwater isohypses was observed, which supports the assumption that the local drainage of groundwater near the site of investigation may be ignored. The local groundwater recharge will vary between the sparsely vegetated open spaces and the areas covered by trees, as could already be deduced from the geophysical survey.

The tritium levels have been determined by CIO for samples taken at 1981-04-01 and by RIVM for the 1984-12-03 samples. Concerning the first date, ^{18}O data analyzed by CIO are also available (see *Fig.5.5*). The tritium levels in the screens of the KV well resulted in vertical profiles, which were compared to the rainfall tritium levels in Groningen in the preceding years, taking into account a possible regional effect. The interpretation of ^{3}H data was based on the presence of a single aquifer with D=100 m and p=0.35, recharged by a uniform infiltration of water, as illustrated in *Fig..5.12* and *5.13*. The interpretation results in:

Fig.5.10. EM-31 values in mS·m^{-1}.



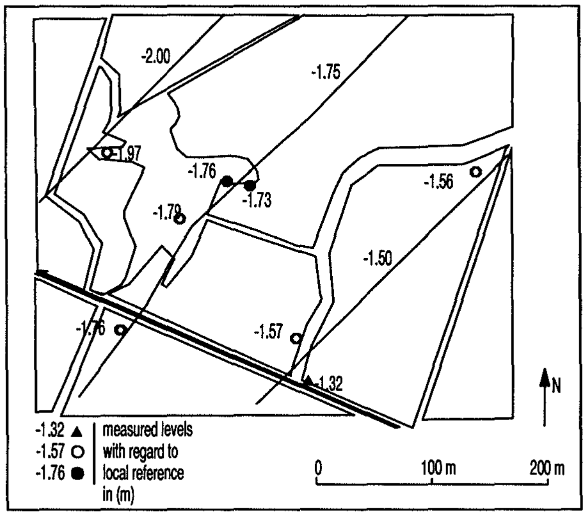


Fig.5.11. Isohypses on 1984-12-03 relative to a local reference.

1981 data: f=1.50 (multiplication factor); 1-year moving average in rain; I/p=1.07 m·a^{-1} (vertical flow rate); I=0.375 m·a^{-1} (groundwater recharge).

1984 data: f=1.50 (multiplication factor); 1-year moving average in rain; I/p=1.07 m·a^{-1} (vertical flow rate); I=0.375 m·a^{-1} (groundwater recharge).

Although the observed values show a marked change in time, both interpretations lead to the same results, supporting the consistency of the determinations. The vertical percolation at the well deviates from the expected recharge in a forest area because of the presence of a sparse vegetation near the observation well. At greater depths, an average flow situation will predominate. The interpreted value of the f-factor is only partly caused by a regional effect. The regional factor, determining the tritium content of local rain, is f=1.15 (according to section 4.2). The conclusion is that other factors cause an additional enrichment of the tritium content. However, surface discharge will not play a role in the given situation. The mean value of the observed ^{18}O data is -7.5 $^{0}/_{00}$ (SMOW) (*Fig.5.5*), which is less than the expected value of –7.9 $^{0}/_{00}$ (SMOW) observed in Groningen rainfall. Although the groundwater recharge is influenced by the location of the observation well in the open space, the sampled groundwater will have the characteristicts of forest groundwater. Most probably, an effect of open water evaporation from rain intercepted by trees is present, whereby both the ^{18}O and the ^{3}H levels (expressed by the f-factor) will increase.

5.2.4 Synthesis of flow patterns

The observed transition in groundwater quality at a depth of about 25 m (VES results, see section 5.2.2) has interesting consequences. If it is assumed that the transition zone marks a groundwater age, corresponding to the planting of the pine forest around the year 1900, the amount of recharge can be derived from the equation for a single aquifer:

I/p=(D/t)*ln(D/(D-z));

with: I= recharge (m·a^{-1}) to be determined;
p= porosity, here p=0.35;
t= time since recharge (years), here t=80 years;
D=total thickness of the aquifer (m), here D=100 m;
z= depth of observation (m), here z=25 m.

Substitution of the indicated values yields I=126 mm·a^{-1}, which indeed is a likely value, if compared to

Fig.5.12. Tritium data 1981.

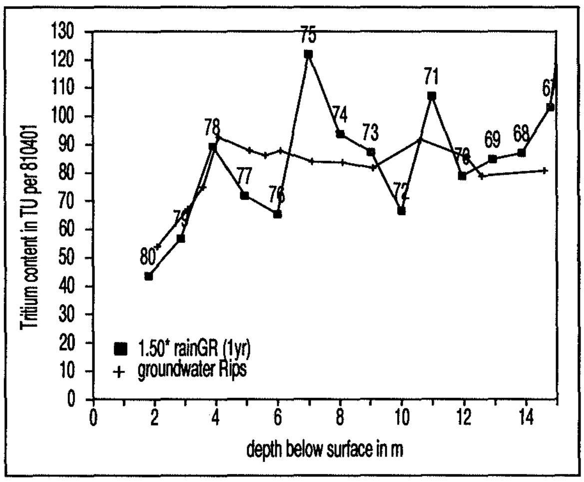
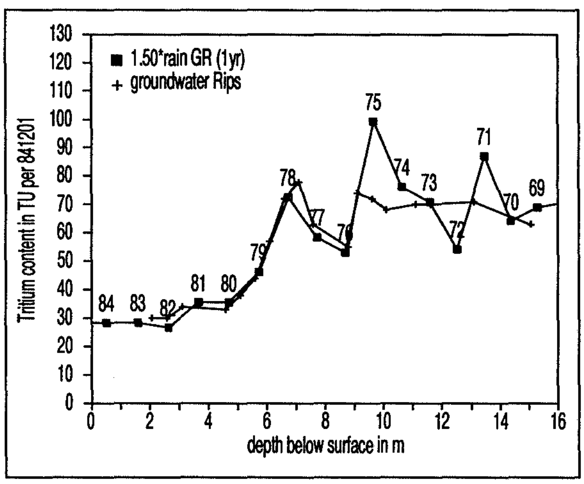


Fig.5.13. Tritium data 1984.



the estimated recharge in a pine forest in the Peel area (section 2.1).

Another indication concerning the flow situation, follows from the EM-31 survey, indicating the thickness of the top layer containing groundwater of low conductivity, which is recharged at the open space. It is assumed that:

- the conductivity of the unsaturated zone with a thickness of 1.0 m is 0.2 $mS \cdot m^{-1}$ in the open space, corresponding to the observed resistivity of 5000 Ωm (VES);
- the conductivity is 1 $mS \cdot m^{-1}$ of the layer of a variable thickness, containing groundwater of low conductivity, corresponding to a resistivity of 1000 Ωm.
- the conductivity of the deeper layer is 3.6 $mS \cdot m^{-1}$ (VES),

By assuming the above conductivities, the increase in thickness of the low conductivity layer in the direction of flow can be estimated from the EM-31 values (McNeill, 1980). The situation at the centre of the open space is represented in *Fig.5.14*. The gradient of the base of the layer is 6:100. The base apparently represents a groundwater flow line with the same gradient, which, theoretically, will be curvilinear, but the approximation by a straight line is allowed. The horizontal velocity can be estimated from Darcy's law, assuming that the permeability is $k=10\ m \cdot day^{-1}$ for the relatively fine dune sand of the upper layers and that the gradient in groundwater heads is 1:600 as follows from the isohypses (*Fig.5.11*). The ratio between the horizontal velocity and the groundwater recharge (I) is 6:100, according to the EM-31 interpretation. After elaboration, it follows that the groundwater recharge at the open space is $I=365 \cdot mm \cdot a^{-1}$. The estimated value corresponds to the value following from the interpretation of the tritium profiles (section 5.2.3), indicating that a value for the porosity of p=0.35 represents a satisfactory approximation.

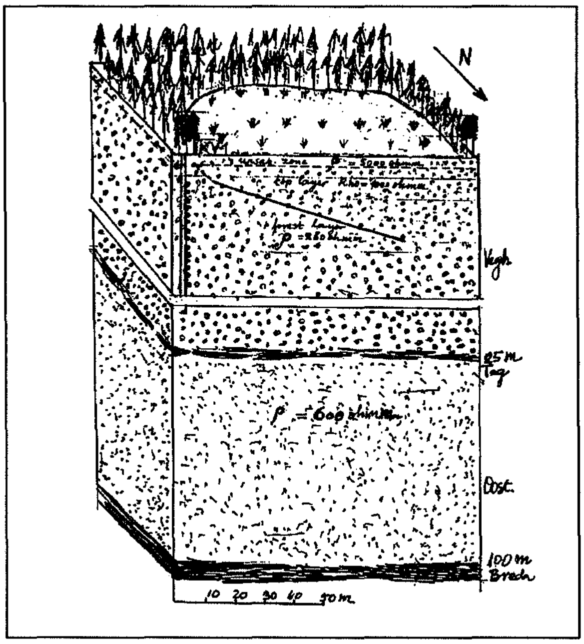
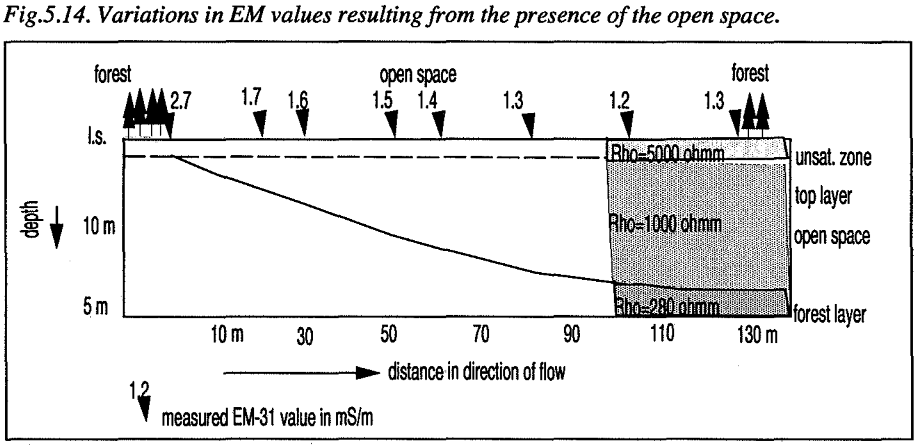


Fig.5.15. Structure of the subsurface in Rips forsest

The groundwater recharge in the open space is relatively high, but not unrealistic given the almost bare soil of the open space (*Fig.5.4*). *Figure 5.15* summarizes the geohydrological situation. A general conclusion from the geohydrological situation at Stippelberg forest is that the groundwater recharge in forest areas may widely vary, depending on the location near, or downstream from, open spaces.

Fig.5.14. Variations in EM values resulting from the presence of the open space.



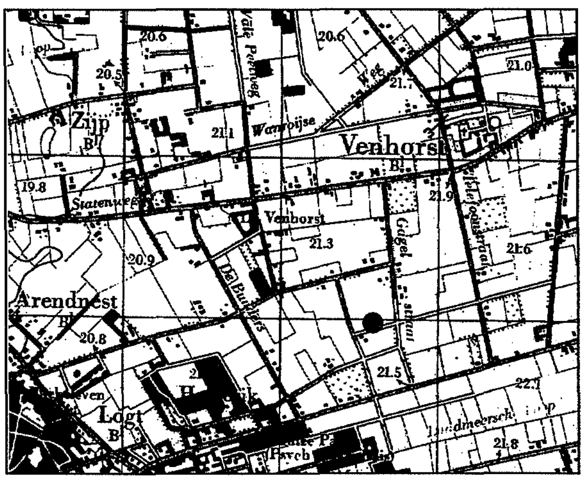
5.3 The Venhorst farmland

5.3.1 The investigated site

The Venhorst farmland in the Peel region (*Fig.5.16*) was reclaimed around the year 1930 (Peters, 1982). One of the farmhouses near the investigated site still bears the date 1926. The land is flat without much habitation and only along the roads were trees planted. The natural surface water system was rudimentary, implying relatively dry conditions in summer periods and wet conditions in winter-time. The hydrological situation in itself did not lead to marshy conditions everywhere. Even at present, the surface water network in the area has been laid in a wide grid. The digging of a few deep ditches was sufficient to turn the wet moorlands of the Venhorst region into a dry agricultural area. The major reason for the land not being reclaimed earlier was probably the poor fertility of the soil, consisting of coarse sand at a shallow depth. After the introduction of fertilizer, the soil could be brought into cultivation. Before reclamation, the land consisted for centuries of scarcely vegetated wasteland with mainly heather and marsh vegetation.

The land has been parcelled in large plots, where, at present, much maize is grown. The farm near the central KV well saw intensive husbandry (*Fig.5.18*) practised for a number of years before the investigation. The investigation team was told that the parcel of land between the farmhouse and the well (*Fig.5.17*) had for some time been used as a storage for excess manure. To this end the parcel had been surrounded by small dikes in order to create a reservoir. As this reservoir did not have a sealing at the bottom, the moisture of the manure could readily percolate into the soil. At the time of the investigation this practice had already been abandoned.

Fig.5.16. Situation of the Venhorst site.



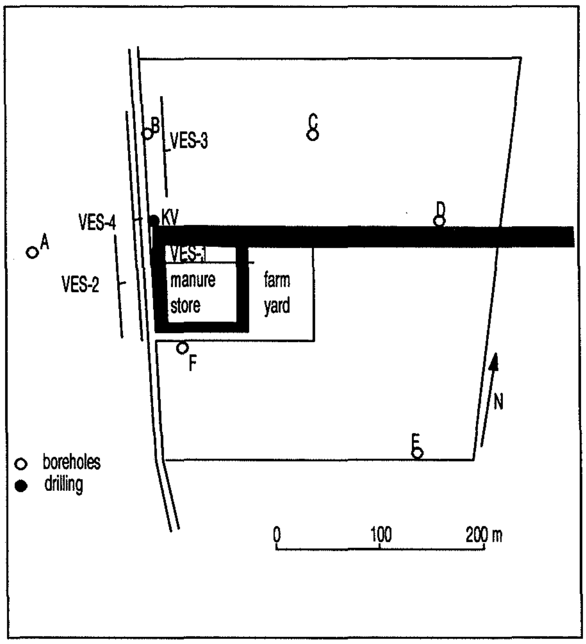


Fig.5.17. The investigations near the KV well.

The additional investigations at the Venhorst farm (*Fig.5.17*) were centered around a KV well. The KV well is a cable-tool drilling to a depth of 20 m, provided with mini-screens at intervals of half a metre. Tritium levels of samples from the KV well at the 1981 sampling round, have been analyzed by CIO, together with the ^{18}O level. For another series of samples, taken in 1983, the tritium level was determined at the RIVM laboratory. In 1985, additional investigations were carried out. At the farm, six shallow boreholes were drilled on 1985-04-02: Groundwater heads were measured and samples taken for chemical analysis. The well heads were surveyed in order to compose groundwater isohypses. Four VES were executed and the surrounding area was covered by a large number of EM-31 observations. The chemical analyses of samples from the KV well (*Fig.5.19*) are also available.

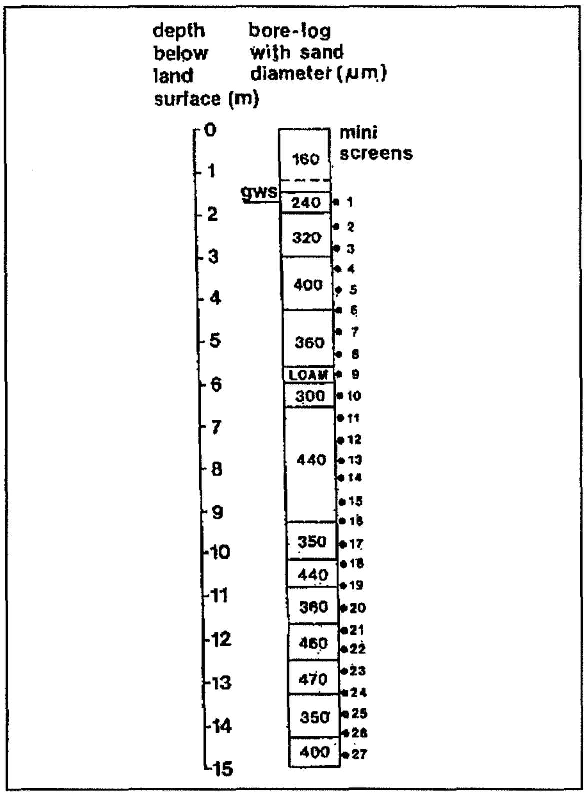
5.3.2 Soil structure and geophysical data

The upper two metres of the soil contain relatively fine sand, probably belonging to the Twente Formation and covering the coarse sand of the Veghel Formation (*Fig.5.19*). VES results are given in *Figs.5.20* to *5.23*. The upper two layers represent the unsaturated zone, the second layer in VES 3 and 4 is probably a layer with less polluted groundwater,

Fig.5.18 . Applying manure to the Venhorst farmland.

which was recharged near roads or at tree lanes. Below the unsaturated zone, the upper aquifer has a constant resistivity, except for an intercalated layer, containing water of high conductivity. That layer represents the heavily polluted groundwater recharged in

Fig.5.19. The KV well data.



the former manure storage. It is lacking in VES Venhorst-3, situated outside the flow traject, where instead, another layer with a low resistivity (loam) is present at a depth of 10 m. The layers to a depth of 23 m contain the normal groundwater recharged in local agricultural lands. At a depth of about 23 m the apparent resistivity of the subsurface increases. The most likely reason is an increased conductivity of the groundwater because of a different origin of the recharge. The layer below 25 m probably contains groundwater originating before reclamation. The deepest layer is the base of the aquifer system, consisting of clayey and loamy layers, presumably of a Tertiary Age. The upper sandy layers form one single aquifer down to a depth of 60 m.

The EM values (*Fig.5.24*) show the effect of a pollution of the soil in the parcel, where excess manure was stored for a number of years. The values of the apparent conductivity, measured with the EM-31 in the polluted area, are in general between 15 and 25 $mS{\cdot}m^{-1}$. At the downstream side, the EM-31 values are ranging from 15 to 20 $mS{\cdot}m^{-1}$. The values are between 8 and 15 $mS{\cdot}m^{-1}$ in the surrounding area. The relatively high values decrease in the direction of flow because of a dipping downward and a dispersion of the zone of high conductivity. If lines of equal conductivity are drawn, a pattern can be distinguished in a westward direction. The pattern also represents the direction of groundwater flow.

An interesting feature is the occurrence of unstable EM-31 values in a relatively narrow zone (*Fig.5.24*). According to the Geonics manual, instability will occur at the presence of burried bodies with limited

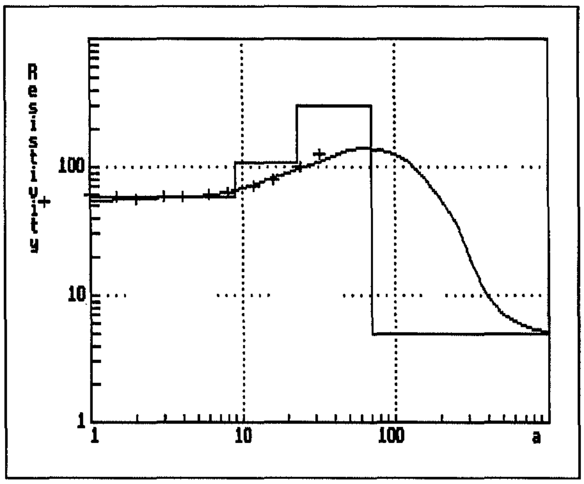


Fig.5.20. VES Venhorst-1.

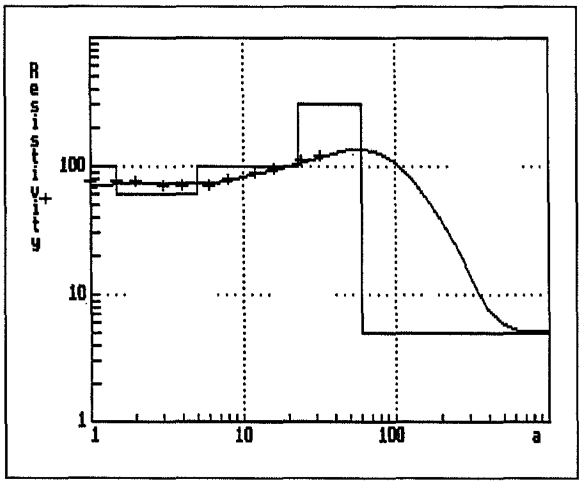


Fig.5.21. VES Venhorst-2.

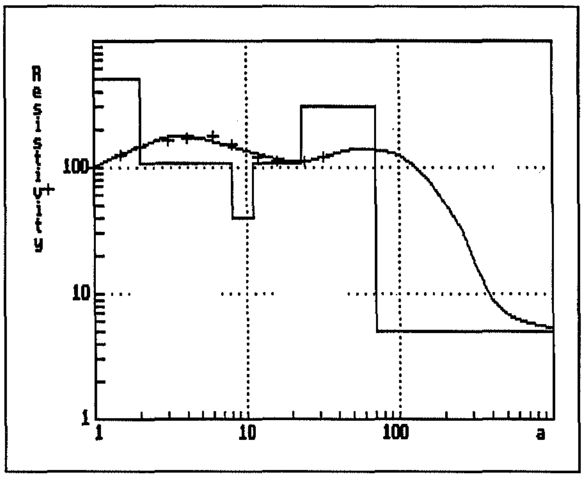


Fig.5.22. VES Venhorst-3.

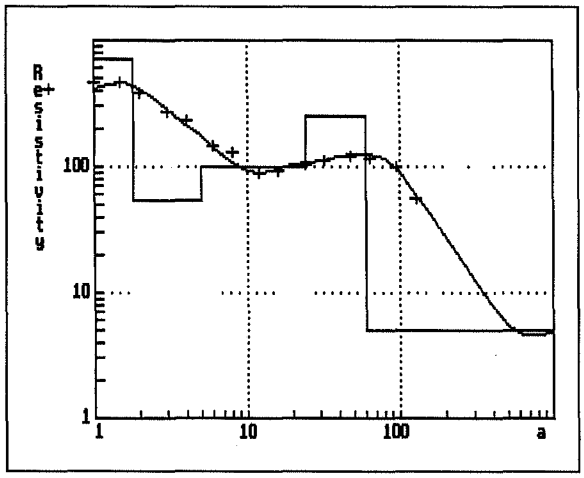
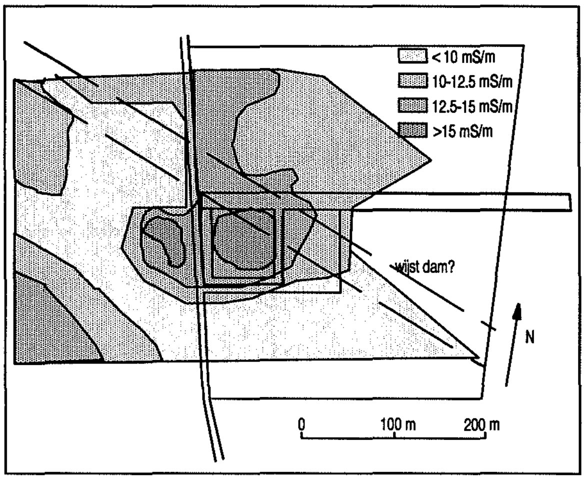


Fig.5.23. VES Venhorst-4.

horizontal dimensions, if compared to the (6-m) reach of the instrument. The zone concerned could represent the presence of an artifact. More likely is the presence of a natural (wijst)-dam in the subsurface, as described by Ernst and De Ridder (1960). A 'wijst dam' follows the direction of a fault and it is caused by the local precipitation in the soil of mainly iron compounds, resulting from a deviating flow pattern. This type of subsurface dam will act as a barrier to the flow of groundwater, implying high levels at the upstream side. Higher groundwater levels would result in higher soil conductivities (*Fig.5.24*). North of the dam, the EM values are indeed slightly more than south of it.

Fig.5.24. EM-31 values in $mS{\cdot}m^{-1}$.



5.3.3 Groundwater recharge and flow

The composition of groundwater isohypses was based on observed levels, by taking into consideration the presence of a shallow barrier. From the pattern of EM values a slightly other direction of groundwater flow can be derived, downstream of the manure storage, than following from the heads. The presence of a 'wijst

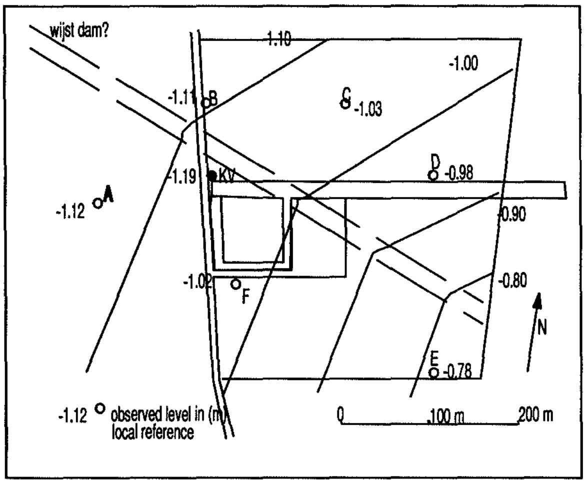


Fig.5.25. The groundwater isohypses on 1985-04-02.

dam' is likely and the map of isohypses (*Fig.5.25*) has been drawn, taking into account the patterns of the EM-31 survey. As a result, the isohypses are curvilinear, with a strong curvature at the location of the supposed 'wijst dam'. The general direction of the local flow is to the northwest, like the regional trend. Groundwater levels are about 1.0 m below surface.

The tritium levels have been determined by CIO for samples taken at 1981-04-01 and by RIVM for the 1983-03-23 samples. For the first date, ^{18}O data, determined by CIO are also available (see *Fig. 5.19*). The interpretation of the ^{3}H data has been based on the presence of a single unconfined aquifer with D=60 m and p=0.35, recharged by uniform rainfall. The interpretation, illustrated in *Figs.5.26* and *5.27*, results in:

1981 data: f=1.15 (multiplication factor); 2-year moving average in rain; I/p=0.83 $m \cdot a^{-1}$ (vertical flow rate); I=0.290 $m \cdot a^{-1}$ (groundwater recharge).

1983 data: f=1.15 (multiplication factor); 2-year moving average in rain; I/p=0.83 $m \cdot a^{-1}$ (vertical flow rate); I=0.290 $m \cdot a^{-1}$ (groundwater recharge).

Although the observed tritium levels differ, the interpretation leads to exactly the same conclusions in both cases, supporting again the consistency of CIO and RIVM analyses. The value derived for the groundwater recharge is in the expected range, assuming that the land is predominantly used for maize cultivation. A first estimate of the recharge, based on the average amount of precipitation and the average reference evapotranspiration is a value of I=240 $mm \cdot a^{-1}$, constituting the average groundwater recharge for arable land under the Peel meteorological conditions. The difference of 50 $mm \cdot a^{-1}$ between the two values corresponds to the expected reduction in the potential evapotranspiration (Werkgroep HELP, 1987). The regional factor is in agreement with the regional factor derived for local rainfall in the Peel area (section 4.2). It should be noted that tritium levels in rainfall, which are represented by two-year moving averages, give the best fit in the comparison with groundwater data. Apparently, the mixing in the subsurface is relatively strong.

The average value of groundwater ^{18}O data at the Venhorst location, amounts to -7.76$^{0}/_{00}$ (SMOW), corresponding to an average value of -7.9 $^{0}/_{00}$ (SMOW) in Groningen rainfall. The conclusion is that the groundwater tritium level has not been subject to any changes during recharge.

Fig.5.26. Tritium data 1981.

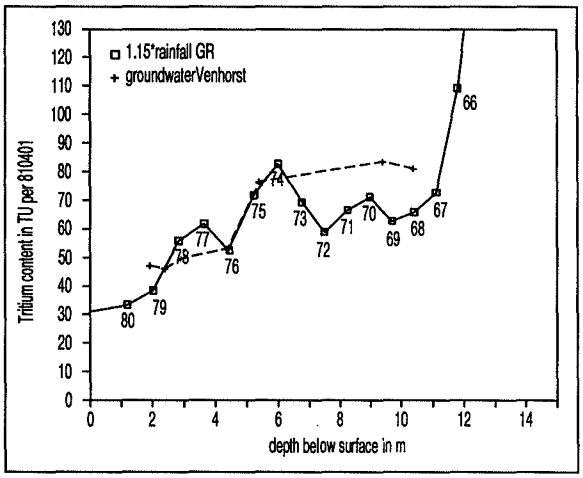
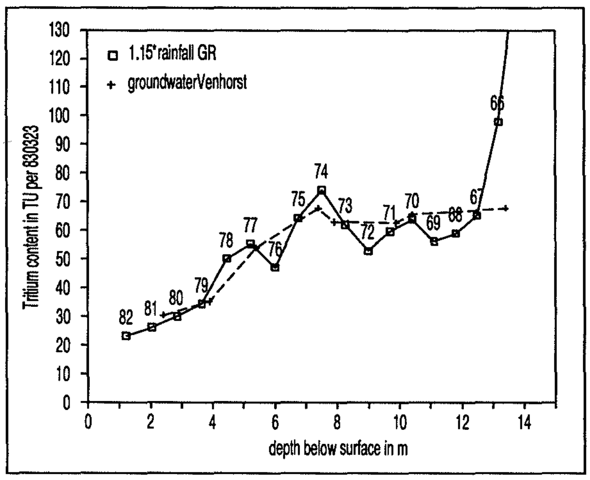


Fig.5.27. Tritium data 1983.



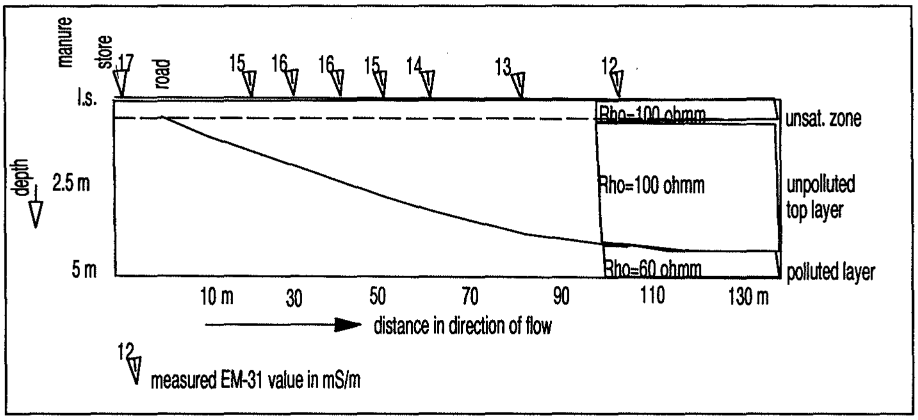


Fig.5.28. Variations in EM values resulting from the presence of the manure deposit.

5.3.4. Synthesis of flow patterns

The geo-electrical measurements showed a transition from a layer with a low resistivity to layers having a higher resistivity (implying the presence of groundwater with lower conductivity) at an average depth of 23 m. By assuming that the transition marks the boundary between groundwater recharged before and after reclamation, and applying the flow equation for a single aquifer, the recharge can be estimated. However, not the supposed date of reclamation is assumed, but the year 1946, marking an intensification of fertilizer use after the Second World War.

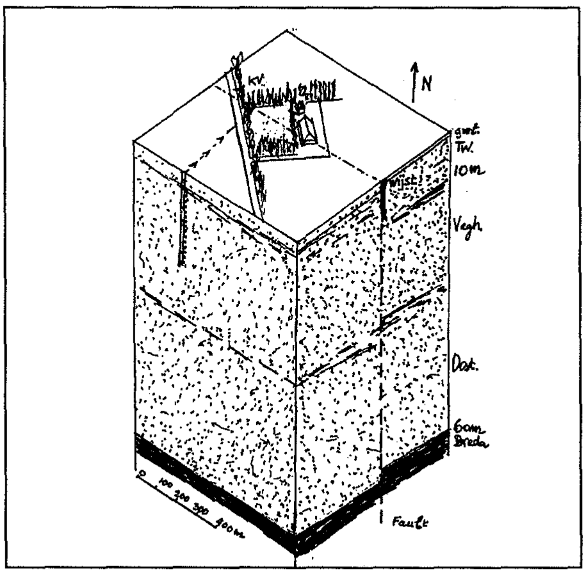
By assuming that a depth z=23 m represents an age of 39 years (1985-1946=39 years) and that D=60 m, it follows that I/p=0.74 m·a^{-1}, implying that the groundwater recharge is I=260 mm·a^{-1} (p=0.35). This value corresponds reasonably well to the estimated recharge of I=290 mm·a^{-1}, derived from the tritium levels. The vertical percolation estimated from the tritium profiles is slightly higher than this value, maybe because of an additional recharge, since the land use changed from the cultivation of traditional crops to the growing of maize.

In the area affected by extra pollution from the manure store, an indication can be obtained of the thickness of an intercalated layer of high conductivity by elaborating the EM-31 survey. By assuming from the VES results that:

- the conductivity of layer 1 with a thickness of 1.0 m is 10 mS·m^{-1}, corresponding to a resistivity of 100 Ωm;
- the conductivity of the deeper layer is 10 mS·m^{-1}, corresponding to a resistivity of 100 Ωm;
- the conductivity of the intercalated layer of a variable thickness, containing polluted groundwater, is 16.6 mS·m^{-1} (VES-4 indicating 60 Ωm);

Now the variation in the top of the intercalated layer in the direction of flow can be estimated from the EM-31 results (McNeill, 1980). The situation at the centre of the polluted zone is represented in *Fig.5.28.* It follows that the gradient at the top of the polluted plume is about 5:100. The top of this layer apparently represents a groundwater flow line with the same gradient. Again, this flow line will theoretically be curvilinear, but in practice it may be approximated by a straight line. The horizontal velocity can be estimated from Darcy's law, assuming that the permeability of the upper layers is k=10 m·day^{-1} and that the gradient in groundwater heads is about 1:1000, as follows from the isohypses (*Fig.5.25*). The horizontal velocity is 100/5=20 times the vertical velocity. Hence, the groundwater recharge is I=182 mm·a^{-1}. The estimated value is (much) smaller than the recharge, resulting from the tritium profile. The reason is perhaps that the estimate of the horizontal permeability is too low. The geohydrological situation is summarized in *Fig.5.29.*

Fig.5.29. Soil structure of Venhorst farm



5.4. The situation at Vredepeel

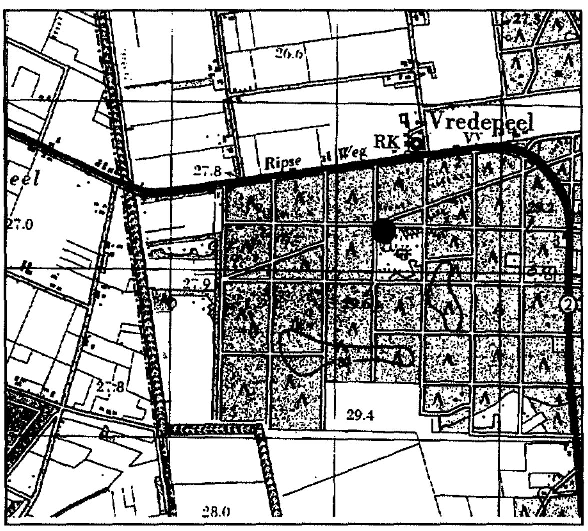
5.4.1 Landscape and investigations

In the years from 1920 to 1940, private farmers and (semi-) government organizations (Heidemaatschappij) started a large-scale reclamation of vast wastelands in the Peel area. Most of the land was turned into agricultural fields, but near Vredepeel (*Fig.5.30*) a pine forest was planted in the 1930s and the Ministry of War established the Peel air force base. A National Groundwater Monitoring Network (LMG) well was constructed near a forest lane, bordering the air field (*Fig.5.31*). Near that well, detailed hydrological investigations were carried out in 1981/82, and again in 1985. The investigations included the drilling of an additional N well to a depth of 20 m, with so-called mini-screens at intervals of 0.5 m, tapping the groundwater in the saturated zone. The screens were sampled during the four seasons of the years 1980-1981; the samples were analyzed and the results compared (Duijvenbooden, 1985). In April 1981, the mini-screens were also sampled to determine the groundwater levels of tritium and ^{18}O (analyzed by CIO).

The investigations in 1985 (*Fig.5.31*) consisted of:

a) Sampling the mini-screens of the N well, in order to analyze the groundwater composition and its tritium content (RIVM laboratories).
b) A geophysical survey in the surroundings of the N well comprised the execution of five geo-electrical arrays (VES) and a coverage of the area around the N well with EM-31 measurements.
c) Screens were installed in six additional boreholes, where samples were taken and the groundwater level measured; the wells were surveyed.

Fig.5.30. Situation at Vredepeel.



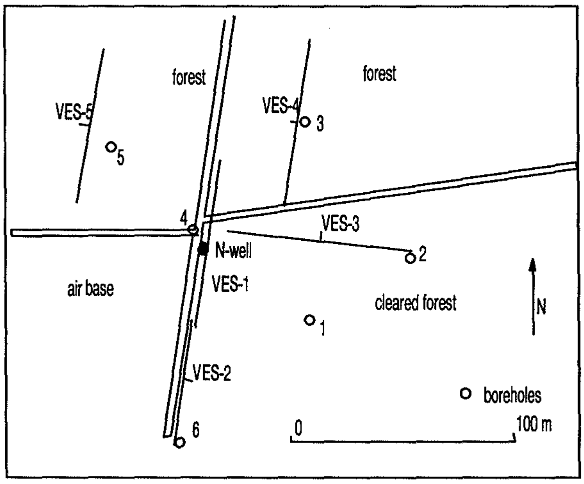


Fig. 5.31. Investigations around the N-well

In 1981, the area near the air field was fully covered by a relatively thinly developed forest, containing broad forest lanes at regular distances. The N well was located on the east side of an open forest lane, bordered on the west side by the air field. A broad zone at the outer fringes of the air field, inaccessible to the investigators, was planted with bushes and trees. In 1985, part of the forest at the east side of the N well had been cleared, showing small differences in the level of land surface (*Fig.5.32*), probably representing the remnants of the former cover sand landscape. At a few hundred metres north of the investigated location, the forest ends and the agricultural lands begin. The changes in the situation, monitored by observations in the years before and after the clearing of the forest, lead to interesting conclusions.

5.4.2. Soil structure and geophysics

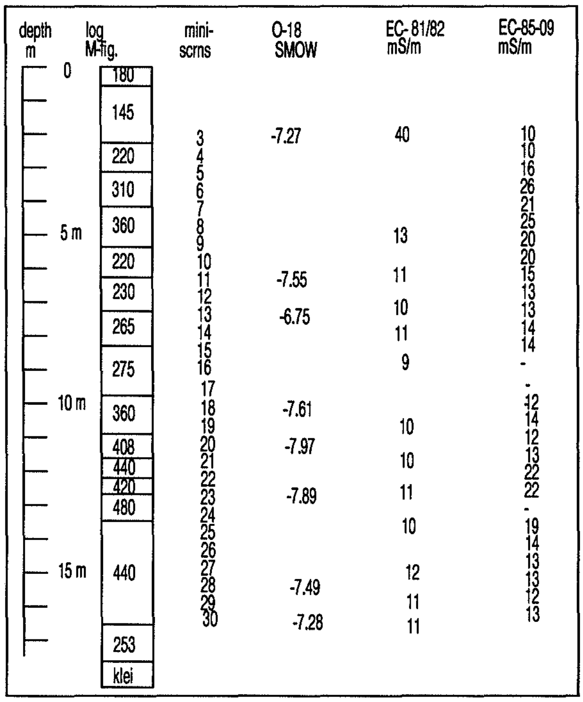
The upper few metres of subsurface (*Fig.5.33*) contain fine sand layers, probably deposited as wind-blown cover sands during the Weichselian cold period (Upper Pleistocene). Below these layers, fluviatile and coarse sands are present to a depth of 17 m, forming part of the Veghel Formation. The drilling of the N well ended in a clay layer with a thickness of some metres, which might represent the Venlo Clay within the Veghel Formation. The structure of the deeper layers can be interpreted with the help of the VES results.

Although the common distances are small, the five VES carried out show marked differences, which are only partly due to variable depths of the water table. Other differences are caused by a layer with an increased resistivity at the top of the saturated zone in

Fig.5.32 . Cleared forest and a lane near the KV well.

some of the VES (*Fig.5.34* and *Table 5.1*). The layer corresponds to the groundwater of lower conductivity sampled from the N well, which represents the groundwater recharged in forest lanes. It may be assumed that the groundwater recharged in an almost bare soil will have a conductivity far less than the values of groundwater recharged underneath trees. A conductivity of EC=8 mS·m^{-1} (at 10°C) in forest lanes, implies a formation factor of F=6; the same formation factor corresponds to a resistivity of 270 Ωm and a

Fig.5.33. Data KV well 81/85.



water conductivity of EC=20 mS·m^{-1} in the deeper layers recharged at the forest (*Table 5.1*). A third difference (*Table 3.3*) results from the variable magnitude of a loam layer at a depth between 15 and 20 m (Venlo Clay), which has a limited thickness.

Another remarkable feature is that the sand layers below a depth of 20 m have a higher resistivity than the upper sand layer. The reason probably lies in an increased resistivity of the groundwater due to a different origin, the lower groundwater having been recharged in a time before the forest was planted. At a depth of about 30 m, the top of a second layer with low resistivities has been interpreted. This layer, having a variable, but being always of a considerable magnitude, most probably represents clay and loam layers of the Tegelen Formation. Below the Tegelen clay layers, a second aquifer is present, again with a relatively high resistivity and resting on loam layers of a Tertiary origin.

The pattern of the EM values (*Fig.5.36*) probably indicates the presence of higher and lower places in a former cover sand area. Not many other conclusions can be drawn from the pattern. A remarkable feature is that the EM-31 values in forest lanes appear to be lower than 1.0 mS·m^{-1}, whereas the values in the vegetated areas are higher. This phenomenon most probably also results from differences in groundwater conductivity. *Fig.5.40* shows the schematical structure of the subsurface. The hydraulic resistance of the clay layer at a depth of 20 m will be relatively small, in contrast to the probably high resistance of the clay layer at a depth in between 30 and 50 m below the surface.

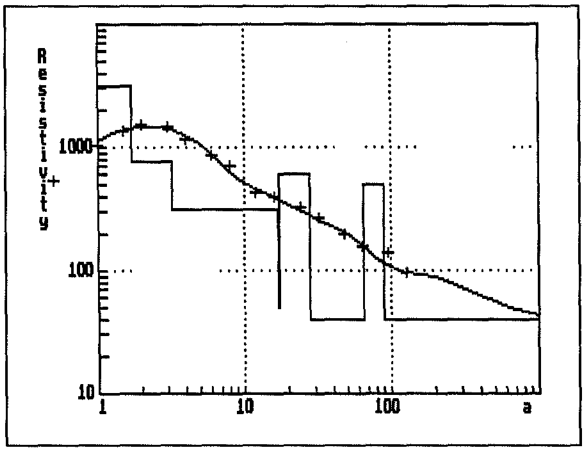


Fig.5.34. VES Vredepeel-1.

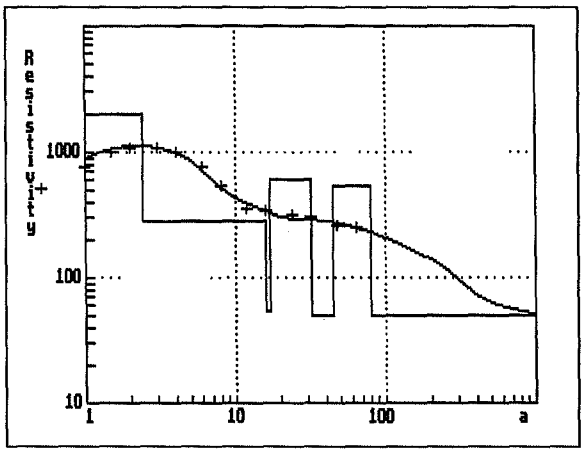


Fig.5.35. VES Vredepeel-3.

5.4.3 Groundwater flow

The groundwater isohypses derived from the measured heads (*Fig.5.37*) indicate a flow in a SSE-NNW direction at a gradient of 1:750, corresponding to the regional trend. The groundwater flow is roughly in the direction of the forest lane, where the N well is situated. The magnitude of the downward groundwater flow follows from the tritium profiles observed at the samples collected in 1981 and 1985 from the N well (*Figs.5.38* and *5.39*). The equation for flow in a single unconfined aquifer is used in the interpretation, assuming the presence of one aquifer with its base at the top of the Tegelen clay layers at a depth of D = 35 m. The approach neglecting the clay layer at 20 m and assuming the clay layer at 35 m as the flow base, agrees with the remarks made in section 2.2.2 concerning a multi-layered aquifer system. The interpretation shows remarkable differences:

1981: f=1.25; I/p=0.857; I=300 mm·a^{-1} (p=0.35);
1985: f=2.1; I/p=0.714; I=250 mm·a^{-1} (p=0.35).

Hence, both the interpreted groundwater recharge and the multiplication factors assume different values for both years. A possible explanation is that the groundwater recharge in both years was different. A factor f=1.25 agrees with the regional trend in the values of annual precipitation. The higher factor f=2.0 (holding for the samples from 1985) might well result from the evaporation of water intercepted by a forest canopy, implying higher tritium levels in the groundwater recharge. This conclusion is supported by the different values for the recharge in both years.

Without modelling, the flow situation is also clear. In 1981, when the forest was still intact, pronounced differences in groundwater recharge existed between the forest area and the open forest lane. At the location of the N well, the groundwater, sampled in 1981, was largely recharged in the forest lane (compare al-

Table 5.1 *Summarized interpretation geo-electrical measurements at Vredepeel.*

	VES-1		VES-2		VES-3		VES-4		VES-5	
layer	dpth	res.	dpth	res.	dpth	res.	dpth	res.	dpth	res.
no.	m	Ωm	m	Ωm	m	Ωm	m	Ωm	m	Ωm
1a	0.4	500	0.5	1000	0.5	500	0.5	500	0.4	700
1b	1.7	3200	3	2900	2.4	2000	1.3	1900	1.6	3000
2a	3.2	750	8	750	-	-	-	-	3.8	750
2b	17	320	17	275	16	280	19	380	18.5	250
3	17.3	50	17.8	50	17	55	20	75	20.5	50
4	28	600	27	600	32	600	30	600	30	600
5	65	40	58	40	45	50	50	50	-	-
6	90	500	90	500	80	550	80	500	80	600
7		40		100		50		100		50

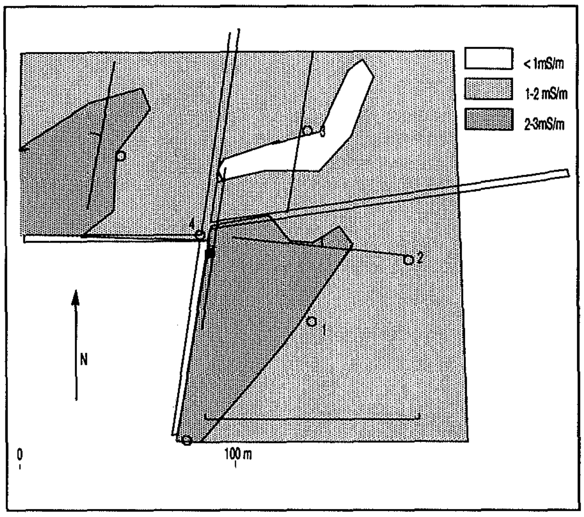


Fig.5.36. EM-31 values in mS·m⁻¹in Vredepeel.

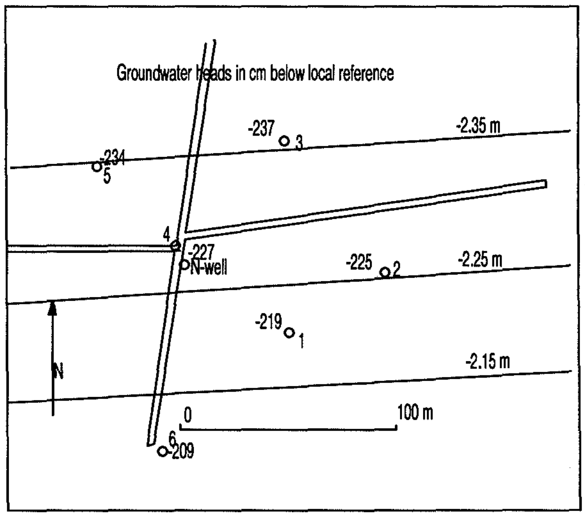


Fig.5.37. Isohypses at 1985-08-12 in Vredepeel.

so section 2.2.3), implying no effect of open water evaporation. In 1985, the forest on the east side of the N well had been cleared, resulting in a similar groundwater recharge in the formerly different areas, but also in a slightly different flow to the sampled screens. The direction of horizontal flow follows from the groundwater isohypses, implying that the groundwater passing the mini-screens in 1985 originated in the fo rmer forest area. The paradox is that at the time when the forest still existed, the sampled groundwater largely consisted of water recharged in open spaces, whereas the clearing of the forest has promoted in 1985 the pumping of water recharged in wooded areas. This conclusion is supported by the other chemical components. The 1981 sampling indicated a significantly lower conductivity (10 mS·m^{-1}) of the groundwater than the 1985 sampling (*Fig.5.33*). A general conclusion from the Vredepeel example is also that the depth of the aquifer has a strong influence on the interpretation of the tritium data and, hence, on the resulting age distribution.

5.5. The former raised bog at Griendtsveen

5.5.1. Landscape and investigations

Peat bogs could locally develop in the Peel region because of very shallow groundwater levels, like at Griendtsveen. The development of a raised bog in the present Griendtsveen area may be explained by its particular hydrogeological situation. The subsurface transport of water was reduced by less pervious layers at a shallow depth and also, the area is near the groundwater divide, implying high water levels due to a lack of draining surface water. An important factor is the presence of nearly impervious clay layers of the Tegelen Formation at a depth of roughly 25 m, reducing the transport capacity of the upper aquifer. The investigated site (*Fig.5.41*), centred around two

Fig.5.38. Tritium data 1981.

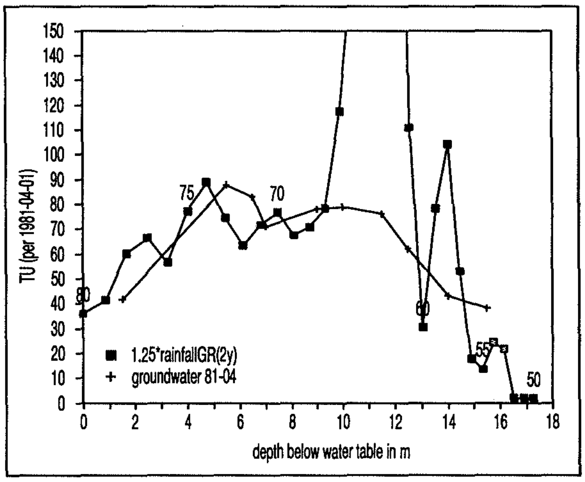
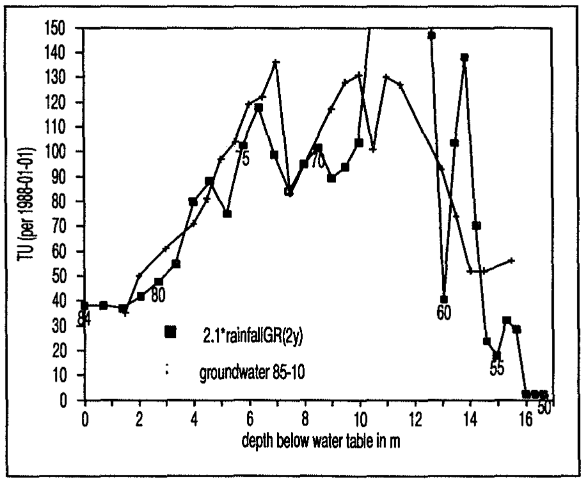


Fig.5.39. Tritium data 1985.



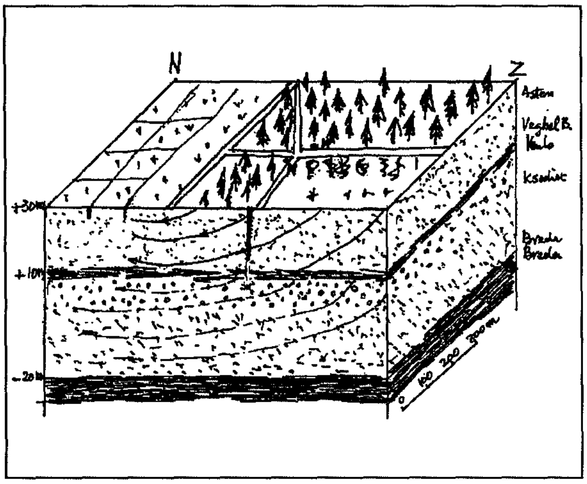


Fig.5.40. Soil structure in Vredepeel.

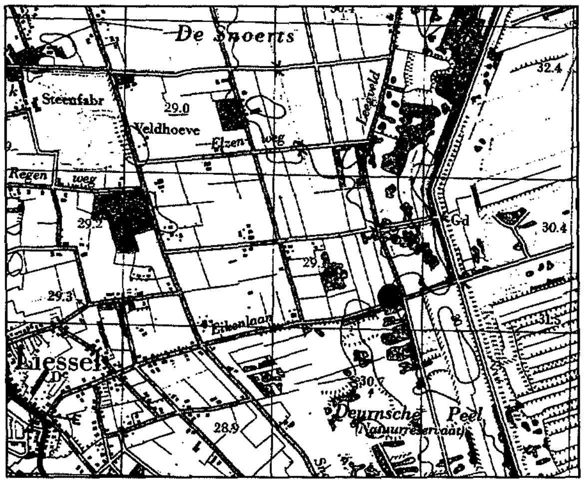


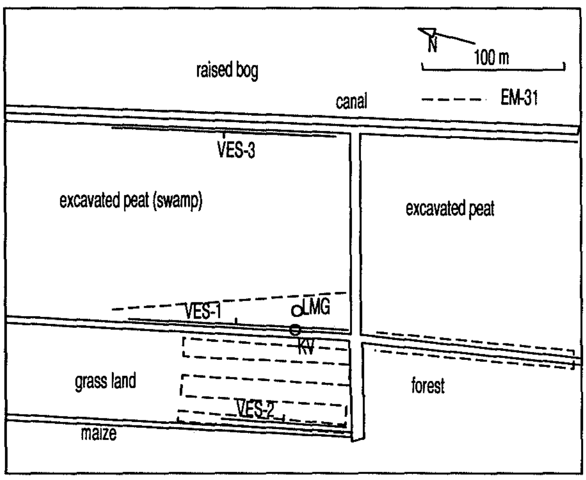
Fig.5.41. The Griendtsveen location.

observation wells (LMG and KV), is situated on the western fringe of the former raised bog.

The road near the wells (*Fig.5.42*) probably marks the boundary of the area where peat was exploited. The land on the west side of the road has been reclaimed for agriculture by reworking the thin peat layers, which were locally present, into the soil. The land is drained by a system of ditches. In the same zone, a small pine forest was planted a few hundreds of metres to the south of the observation wells. On the east side of the road, the peat was excavated for exploitation. The land was not reclaimed for agriculture, but remained a swampy area. At present, the area is a nature reserve, where peat growth is stimulated again by maintaining wet conditions and a dense vegetation of sphagnum moss, grass and bushes, producing many organic residues. In the area east of the canal, part of the peat layers were excavated, but not all of it, leaving large ponds in a peat soil. Also in that area, peat growth is stimulated by keeping the water level close to land surface, which is a few metres above the land surface in the area west of it.

The investigations (*Fig.5.42*) were carried out around a well of the National Groundwater Monitoring Network (LMG) and a nearby KV well. The KV well is a cable-tool drilling, with mini-screens at intervals of half a metre, to a depth of roughly 15 m. In 1981-1982, the KV well was sampled in all four seasons in order to investigate the chemical composition of the groundwater. Samples were also taken on 1981-04-03 for the determination of ^{18}O and tritium levels by CIO. In April 1983, another series of samples was collected for an analysis of tritium levels by RIVM. At the same time, samples were taken for the determination of the deuterium (^2H) and ^{18}O levels by CIO. The aim of the latter investigation was to research a possible open water evaporation, occurring before groundwater recharge. In 1985, three VES were executed and the area surrounding the two wells was covered by an EM-31 survey.

Fig.5.42. Investigations near the KV well.



5.5.2. Soil structure and geophysics

The soil samples from the KV well (*Fig.5.44*) indicated a thin peat layer at a shallow depth, which probably is a remnant of the former peat cover. Below that layer the subsurface contains fine sand to a depth of 7 m, which is underlaid by layers with relatively coarse sand. The VES interpretation showed a larger variation. In VES-1 (*Fig.5.45*), a layer of fine material was detected at a depth of roughly 4 m below the surface, possibly containing peat. The second layer in VES-3 below the unsaturated zone, to a depth of roughly 2 m, has a low resistivity, representing unexcavated peat layers. Another layer with a rel-

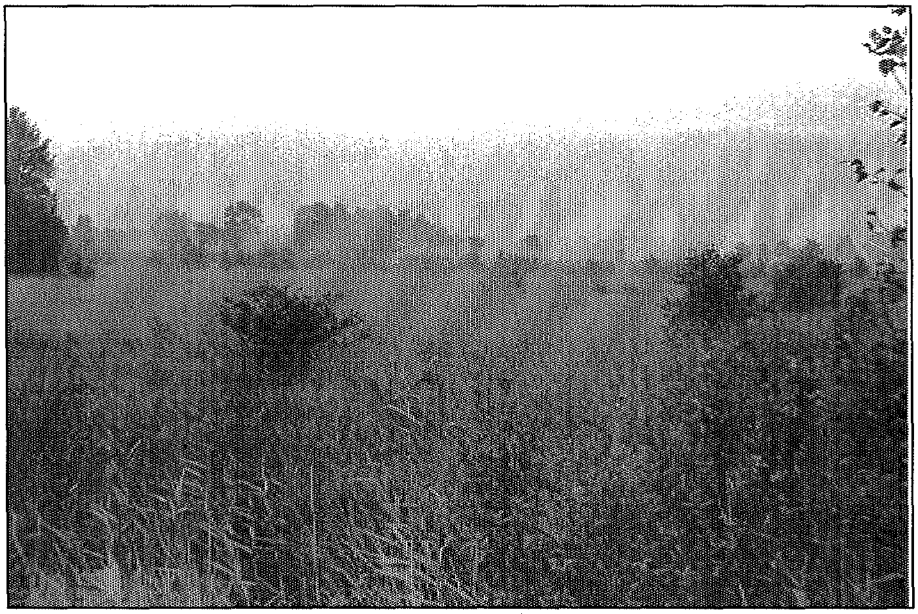


Fig.5.43. The zone where the peat was excavated.

Fig.5.44. Grain sizes; ^{18}O data.

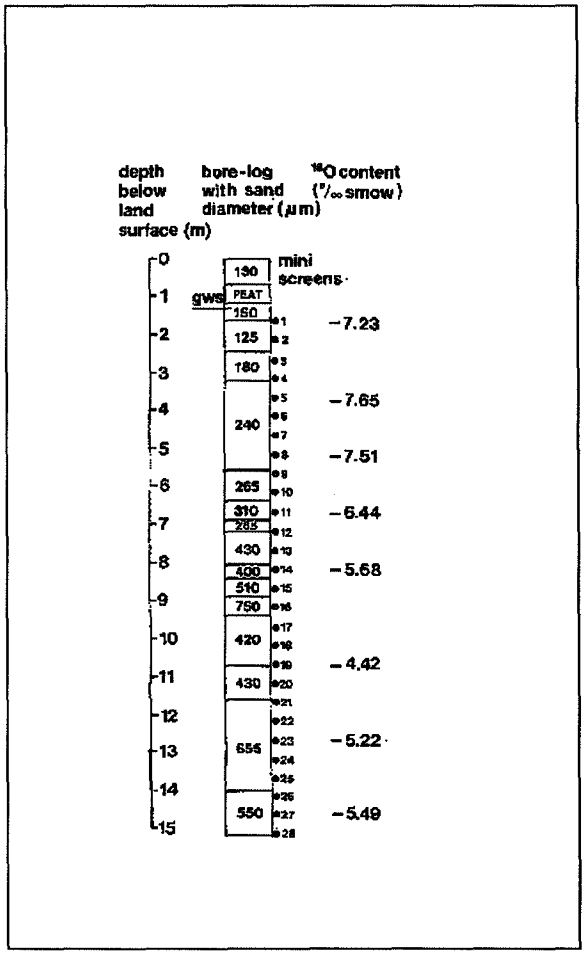


Fig.5.45 VES Griendtsveen-1.

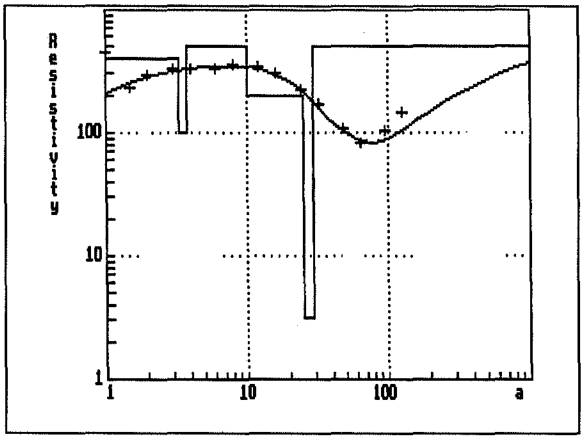
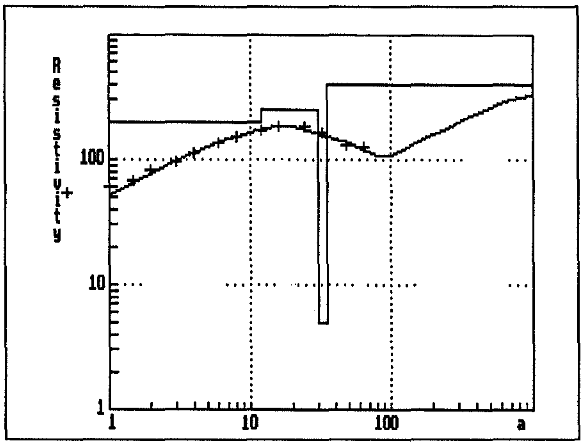


Fig.5.46 . VES Griendtsveen-2.



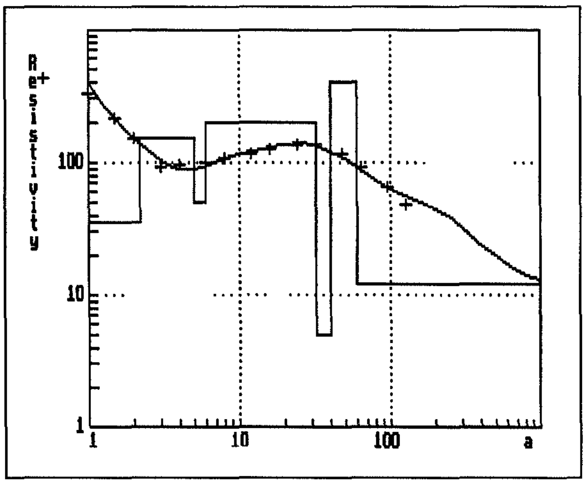


Fig.5.47. VES Griendtsveen-3.

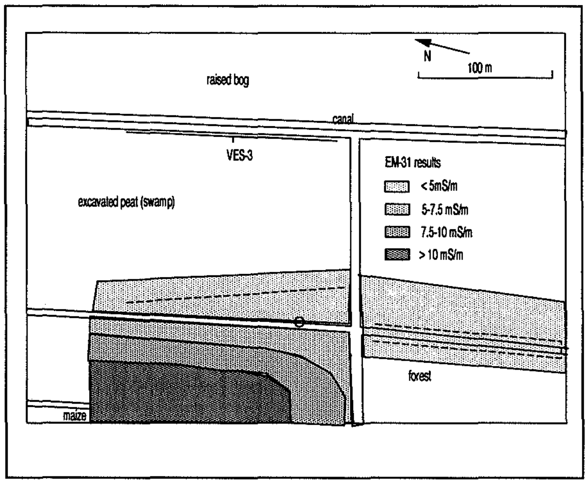
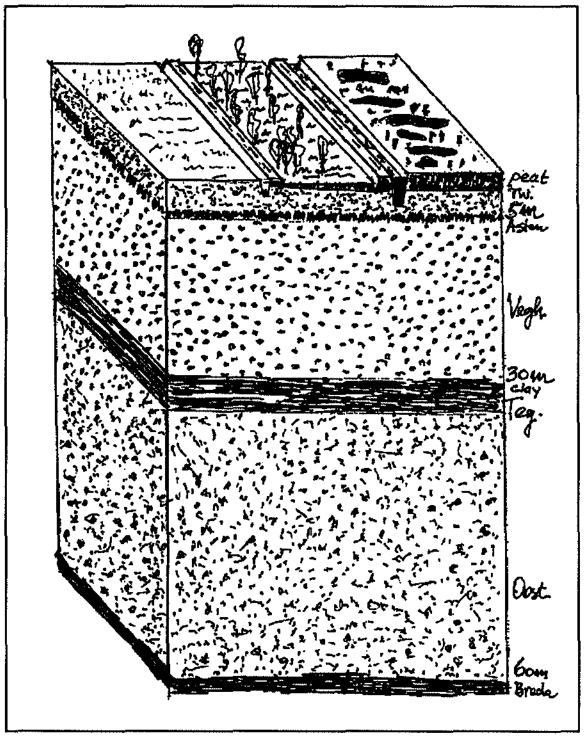


Fig.5.48. EM-31 results

atively low resistivity is interpreted at a depth of 5 m in VES-3, which probably is the same layer as detected in VES-1. Both the shallow peat layer and the layer at a depth of 5 m are lacking at VES-2. A remarkable difference between VES-1 and VES-2 concerns the resistivity of the upper sand layers, which in VES-1 is roughly two times the value of the same layers in VES-2. The difference is related to the groundwater composition, which in VES-2 is affected by soil pollution, due to the use of fertilizer and large amounts of manure.

Fig.5.49 Soil structure in Griendtsveen.



Below a depth of 5 m, coarse sand has been deposited to a depth of roughly 20 to 30 m, where the top of clay layers, presumably belonging to the Tegelen Formation is interpreted. Another set of sand layers is present from a depth of 25 m to some 70 m. The deeper subsurface is similar at all VES, but the depth of the base remained undetermined in VES-1 and VES-2.

The EM-31 results (*Fig.5.48*) clearly indicate the effects of a groundwater composition changed by fertilization. The values for the agricultural land are twice as high as for the nature reserves. Along the east and the south fringes of the agricultural parcel, the EM-31 values are relatively low, indicating a groundwater flow from east to west. Conclusions with regard to the soil structure cannot be drawn.

In a geological sense, the upper fine sand layers are probably cover sands, belonging to the Twente Formation. The peat layer at a depth of 5 m may form part of the Asten Formation and the coarse layers below it are part of the Veghel Formation. The clay layers at a depth of roughly 20 m belong to the Tegelen Formation; they are not very thick, but their resistivity is low, indicating very compact clay layers. The sand layers below 20 m belong to Lower Pleistocene and Tertiary formations, and the even deeper base consists of Tertiary clay and loam layers, maybe also containing fine sand.

The Tegelen clay layer probably forms the base of the shallow groundwater flow. It may be expected that groundwater recharge is limited in the zone with peaty soils, but also in the low-lying zone, because of a high evapotranspiration by phreatophytes. No local groundwater isohypses were observed, but the regional groundwater flow is from east to west (*Fig.5.1*). The geohydrological structure of the subsurface is summarized in *Fig.5.49*.

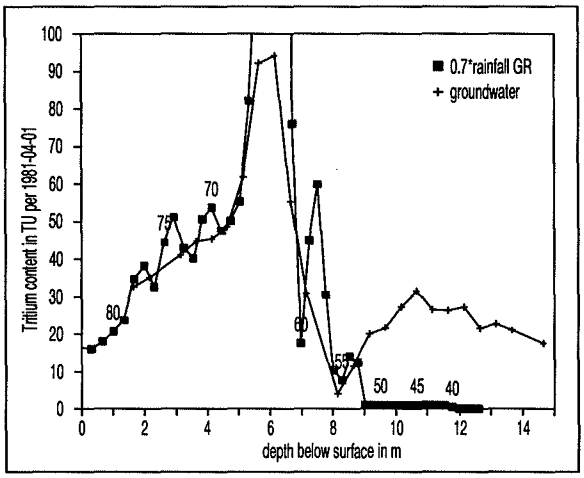


Fig. 5.50. Tritium data 1981.

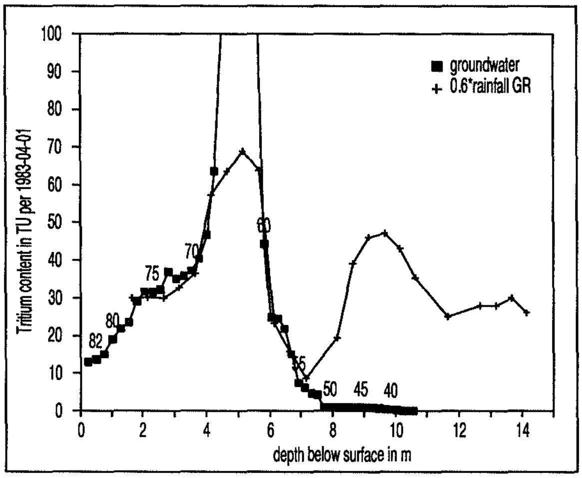


Fig. 5.51. Tritium data 1983.

5.5.3. Groundwater flow

Samples were taken from the KV well (*Fig.5.42*), with mini-screens to a depth of 15 m below surface and analyzed with regard to natural isotopes. Tritium levels were determined by CIO in samples taken at 1981-04-01 and by RIVM for the 1983-03-23 samples. For both dates, ^{18}O data, analyzed by CIO, are available (for 1983 in combination with ^{2}H data) (*Fig.5.52*). Interpretation of the ^{3}H data (*Figs.5.50* and *5.51*) has been based on one single aquifer where D=30 m; p=0.35:

1981 data: f=0.70 (multiplication factor); 2-year moving average in rain; I/p=0.33 m·a^{-1} (vertical flow rate); I=115 mm·a^{-1} (groundwater recharge).

1983 data: f=0.60 (regional factor); 5-year moving average in rain; I/p=0.27 m·a^{-1} (vertical flow rate); I=95 mm·a^{-1} (groundwater recharge).

The observed values show a remarkable trend in time. The peak in concentrations seems to have risen between 1981 and 1983, resulting in a slightly smaller value for the average recharge in 1983. Moreover, in the observed profiles, two parts can be distinguished; the interpretation has focused on the upper part, above a depth of 7 m. Both interpretations lead to comparable results. The groundwater recharge is low in both cases, implying other forms of discharge. The factor f is much smaller than was expected on the basis of the regional effect in local precipitation, which is f=1.20. An effect of open water evaporation is less likely, as that phenomenon would lead to an enrichment of the isotope levels, including tritium. The most probable explanation is that the summer evapotranspiration by phreatophytes will consume the full summer precipitation and a part of the precipitation in the six months of winter, including a removal of the heavy isotopes in rainfall.

The observed ^{18}O and ^{2}H data below a depth of 6 m (*Fig.5.52*) show the effect of open water evaporation (in the peat area). Values deviate in the predicted sense from the Meteoric Water Line, represented by the relationship (Mook, 1989):

Fig.5.52. ^{18}O and ^{2}H data from the KV well, 1983.

depth m	mini-scrns	-O-18 SMOW	-H-2 SMOW
l.s			
	I	8.08	54.1
	2	7.96	
	3	8.15	
	4	7.89	
	5	7.98	
	6	7.35	
	7	7.54	
5 m	8	7.50	
	9	7.16	
	10	6.64	
	11	6.56	45.9
	12	6.64	
	13		
	14	6.76	
	15	6.31	45.1
	16	6.23	
10 m	17	6.18	43.0
	18	5.84	
	19	5.71	38.6
	20	5.13	
	21		
	22		
	23	5.51	40.3
	24	5.78	
	25	5.48	40.3
	26	5.49	
15 m	27	5.58	39.6
	28		

$[^{18}O]=8*[^{2}H]+10$.

The effect is not as clear, or even absent, in the upper layers. At mini-screen no.1, the values are on the Meteoric Water Line. The ^{18}O levels in screens to a depth of roughly 5 m correspond to the expected values in precipitation, no deuterium values being determined. The 'normal' values in the upper zone have to be explained by high evapotranspiration rates, yet without a large open water evaporation. Probably, the groundwater at a greater depth is relatively younger, because the ^{3}H levels are higher, if compared to the upper layer, but data are lacking for a detailed analysis.

Areas with thick peat layers in the shallow soil are nowadays rare in the sandy regions of the Netherlands. The Griendtsveen example shows that great care should be taken in the determination of groundwater recharge and travel times in peaty areas based on an interpretation of isotopic data.

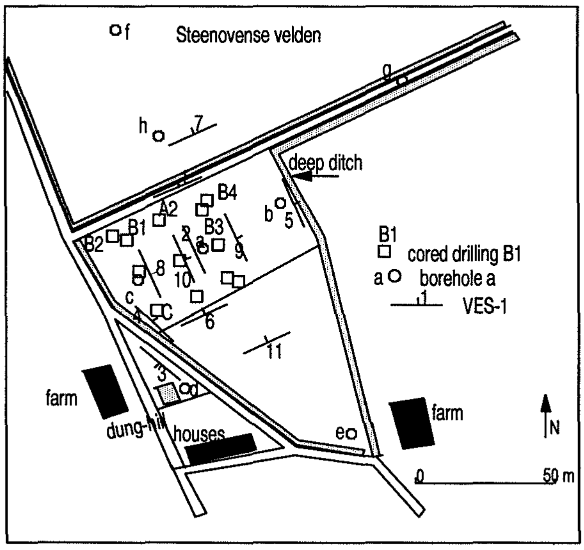


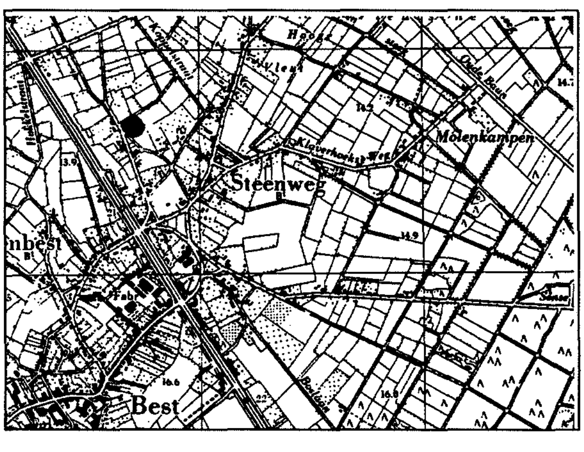
Fig.5.54. The investigations.

5.6. The test location at Best

5.6.1. Situation and investigations

The test location (*Fig.5.53*) in Best is situated in the neighbourhood Verrenbest, traditionally consisting of a patchwork of arable land surrounded by roads where farms were located. To the north, this area was bordered by a marshy area, indicated by the name 'broek' (=wetlands). In between the cultivated and the marshy land was a small zone formerly called the 'Steenovense Velden'. The Dutch word "steenoven" means a traditional brickwork kiln, but nothing was left of any brickwork factory. The drier, non-cultivated fields were, in the old days, indicated by 'velden' (=fields) often used for grazing. The test location forms part of these 'velden'. Currently, the land is used for pasture, alternating with maize cultivation for fodder (*Fig.5.55*). Land parcelling has not been changed in recent years. Land drainage is by small ditches, which are dry in summer. In the winter-time they may be filled with water. On the east side of the test location, a deep ditch, always containing some water (domestic waste water), is present.

Fig.5.53. The location at Best.



Due to a subsiding subsurface, the Quaternary sediments reach a thickness of several hundreds of metres at the site of the test location. At a depth of 80 to 100 m, clay layers of the Kedichem Formation are expected. Above that depth and up to the investigated layers, mainly sand layers of the Sterksel Formation of a Middle-Pleistocene Age, acting as a semi-confined aquifer with a large transmissivity, are present. The younger sediments, reaching to a depth of 20 to 30 m, were mainly deposited by local streams and by the wind. Coarse sand layers were no longer deposited, but instead a series of fine sand, loam layers and organogenic material. The whole series has been called the Nuenen Group in geological terminology.

The Best test location was under investigation from 1982 to 1986. One of the first studies was based on the execution of 12 drillings (A,B,C), placed in a square of 40 m by 40 m (*Fig.5.54*), where cored samples were taken to describe the soil for a sedimentological analysis. The drillings, with a depth from 20 m to 30 m, were carried out by a contractor following the Ackerman system. Most of the cored drillings have been provided with pump and observation screens; well C was provided with mini-screens. The screens were used to execute six pumping tests at three different depths. Groundwater samples from all screens were chemically analyzed at the RIVM labor-

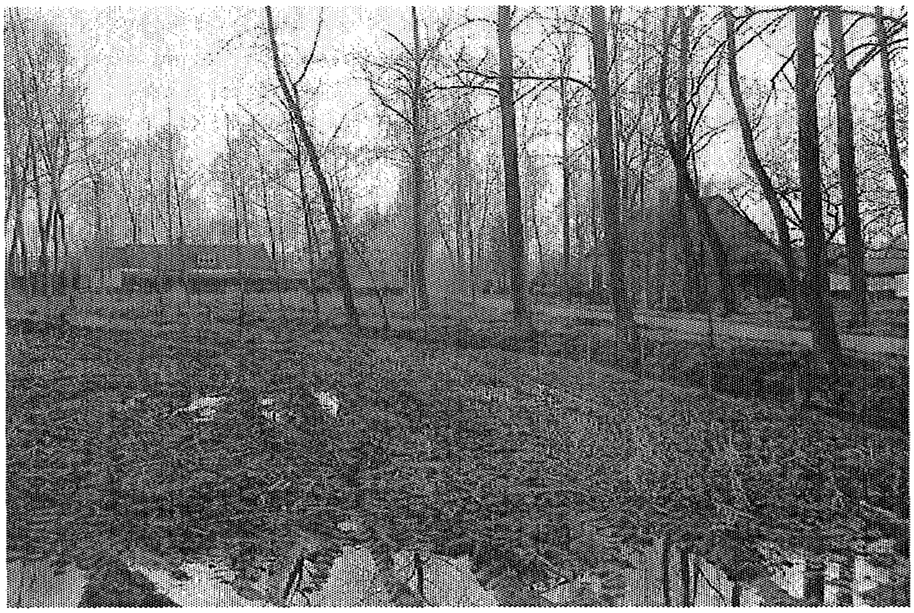
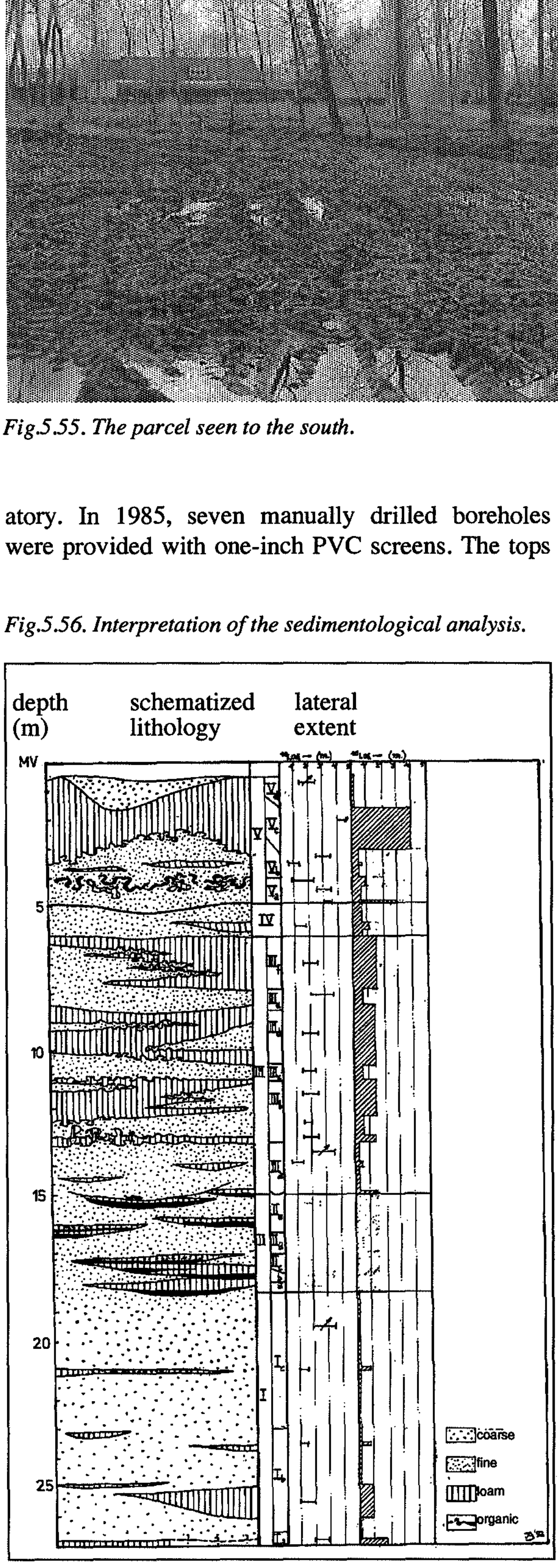


Fig.5.55. The parcel seen to the south.

atory. In 1985, seven manually drilled boreholes were provided with one-inch PVC screens. The tops of the pipes were surveyed relative to a local reference level and the water heads measured. Samples were taken from these wells and analyzed to determine the major chemical elements. In 1983, samples were taken from the mini-screens in well C and the tritium levels analyzed. Eleven VES were carried out in the relatively small area of the test location, which also was covered with EM-31 measurements.

Fig.5.56. Interpretation of the sedimentological analysis.



5.6.2. Sedimentological analysis

The sedimentological features of the cored drillings have been interpreted by Van Alphen (1984). He distinguished major units, deposited in the same environment, which he subdivided in lithologically similar layers. The interpretation is summarized in *Fig.5.56.*

- The base unit, underlying the Nuenen Group of sediments, consists of coarse sand layers of the Sterksel Formation. The boundary between the base layer and the Nuenen Group did not become clear from the drillings, because most of the drillings did not reach the top of the base layer, which is probably situated at a depth of 30 metres below surface.
- Unit I is the deepest of the Nuenen Group. Found between the base layer and a depth of about 19 m, it is a series of sand and loam layers, probably deposited in the Elster glacial period (see also section 1.2). Three layers are interpreted: a loam layer(Ia), an intercalation of loamy and sandy sediments (Ib) and a layer of mainly sandy deposits (Ic). The sand at a depth of roughly 20 m is

relatively coarse and deposited in relatively thick sublayers.

- Unit II, at a depth between 19 m and 15 m, shows a layering of peat (IIa and IIc), sand and loam. A paleosol has developed in some of the layers. Unit II originated in a relatively warm period, probably the Holstein interglacial period (section 1.2).
- Unit III, between 15 m and 6 m below land surface, contains a great number of loamy elements, intercalated with sandy sublayers. Some of the sand has the features of an eolian deposition, but mostly combined with local fluviatile sedimentation. In the samples of this unit many deformations, related to cold conditions like ice wedges, cryoturbation and loadcasting phenomena, were noticed. Presumably, unit III was largely deposited in the Saalian glacial period.
- Unit IV is a relatively thin sandy layer, containing a clearly recognizable paleosol at a depth of some 5 m, developed during the Eemian interglacial period.
- Unit V, the most shallow unit, reaching to a depth of 5 m below surface, contains two layers at the bottom, which consist of loam and loamy fine sand. In the samples a few paleosols and some cold weather deformations could be recognized. At varying depths between 1 m and 4 m below the surface, a relatively thick loam layer, Vc, has been found, with an abrupt transition to the overlying fine and loamy sand layers. Unit V was formed in the cold Weichselian period.

A great advantage of the sedimentological analysis is that the lateral extent of the various deposits can be estimated (*Fig.5.56*). The sandy layers of layer Ic (20 m) probably have very large dimensions in all directions, as these layers were deposited by braided local streams. The peat deposits of unit II (18 m) have a discontinuous character, although they may be expected to occur over vast regions. The loamy layers of unit III (6-15 m) have probably been deposited in local wet depressions and therefore will have limited horizontal dimensions. The loam layer, Vc (1-3 m), will have very large dimensions in all directions as it is assumed to have been formed in a large basin.

Fig.5.57. VES BEST-1.

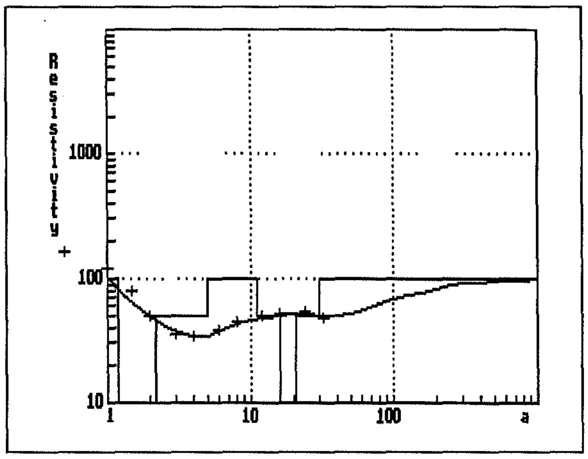


Fig.5.58. VES BEST-2.

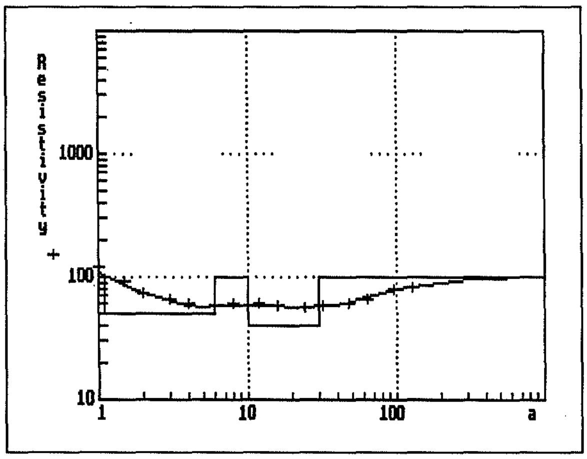


Fig.5.59. VES BEST-3.

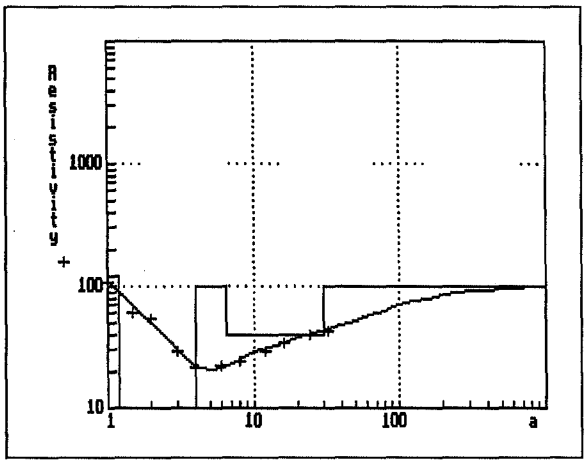


Fig.5.60. VES BEST-5.

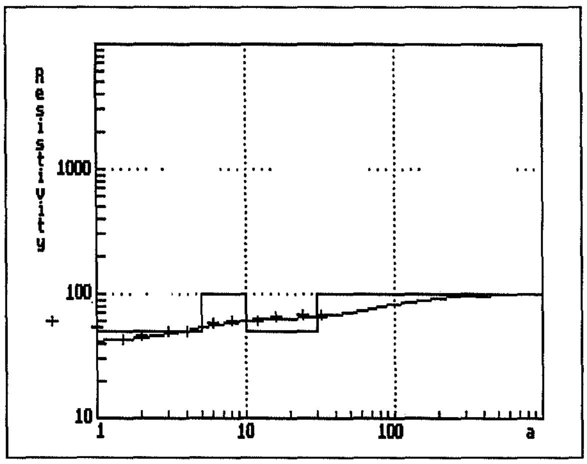


Table 5.2. Results of the interpretation of the VES at Best

	Best-2		Best-3		Best-4		Best-5		Best-6	
layer	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm
1a	0.5	150	0.5	160	0.5	120	0.3	100	0.5	200
1b	1.1	100	1.1	120	1.0	100	0.8	30	1.8	150
2a	-	-	4	10	1.5	20	-	-	-	-
2b	6	50	-	-	4	50	5	50	4.5	50
3	10	100	6.5	100	9	20	10	100	7	100
4a	-	40	-	40	-	40	-	50	-	40
4c	30	40	30	40	30	40	30	50	30	40
5		100		100	100		100		100	

	Best-7		Best-8		Best-9		Best-10		Best-11		Best-1	
layer	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm
1a	0.9	100	1.0	120	1.0	80	1.0	200	0.3	130	0.5	160
1b	-	-	1.5	25	-		2.0	100	1.3	160	1.2	100
2a	2	25	3	50		-	-	-	-	-	2.2	10
2b	4	50	6	20	6	50	6	50	8	50	5	50
3	6.8	100	10	50	9	100	9	100	11	100	10	100
4a		50		50		50	13	50	19	50	17	50
4b		50		50		50	16	10	25	11	20	10
4c	25	50	25	50	25	50	30	50	30	50	30	50
5		100		100		100		100		100		100

5.6.3. Geophysical measurements

The reasons for carrying out many VES at the location were twofold:

1. To elaborate on the sedimentological study.
2. To further investigate the extent of a zone containing groundwater with high conductivity in the subsurface.

The interpretation of the VES (*Table 5.2* and *Figs 5.57-60*) reflects the complicated structure of the shallow subsurface. The schematization into so many sublayers would not be justified if less information had been available. Layers 1a and 1b represent the unsaturated zone, mostly developed with sand, but probably consisting of clay in the case of Best-5. Layer 2a represents a shallow clay layer, clearly present in Best-1, 3, 4 and 7, but lacking in the centre of the area. Layer 3, with a resistivity of 100 Ωm is notable, insofar as the most common resistivity of the Nuenen Group appears to be 50 Ωm (DGV-TNO, 1970), also as observed for layers 2b, 4a and 4c. Coarse sand layers were not described at the depth concerned by the sedimentological analysis, although the soil laboratory determined slightly larger grain sizes. The presence of soil pollution is clearly shown by some VES, like Best-1 (17-20 m), Best-3 (1-4 m) and Best-10 (13-17 m), in the form of a distinct layer with a significant lower resistivity than was expected. Apparently, the polluted layer dips downward in a northerly direction. At a few locations, loam lenses (layers 4b) were interpreted in the deepest part of the Nuenen Group; the loam lenses probably have an irregular character. The top of the base is interpreted at a depth between 25 m and 30 m. The base layer has a resistivity of 100 Ωm, implying that it consists of sandy sediments.

The EM-31 values (*Fig.5.61*) vary between 12 and 40 $mS{\cdot}m^{-1}$, even with a few higher values. Values between 16 and 20 $mS{\cdot}m^{-1}$ are the most commonly measured. The highest values, more than 30 $mS{\cdot}m^{-1}$ are observed underneath and around a traditional dunghill, which in a previous study (Meinardi, 1984) was already indicated as a source of groundwater pollution. Low values of less than 16 $mS{\cdot}m^{-1}$ are present in the centre of the investigated parcel. The boundaries are straight lines, which are often parallel to the parcel boundaries; the configuration suggests an anthropogenic origin of the low values. An interesting possibility is that the low values were caused by the excavation of surficial clay layers for brick manufacturing in a former brickwork kiln. Additional

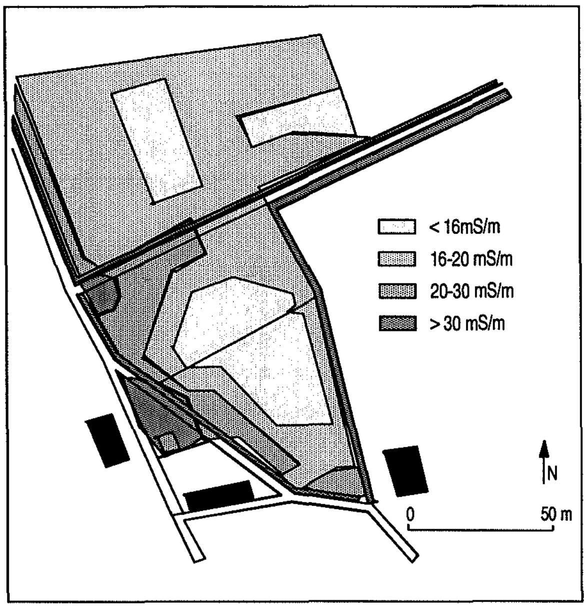


Fig.5.61. EM-31 values in mS·m⁻¹.

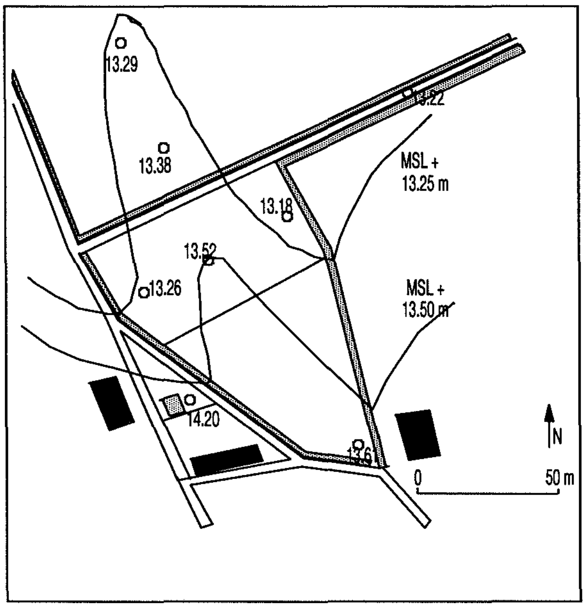


Fig.5.62. Groundwater heads; isohypses (850328)

arguments in favour of this assumption are:

a) Land surface at the parcel is some 0.5 m lower than in the surroundings (*Fig.5.55*).
b) VES measurements in the same area indicate the absence of surficial clay layers.
c) The sedimentological studies concluded at an abrupt transition between the uppermost sand layer and the loam layers underneath.

The shallow soil pollution will result in a strong increase in the EM-31 conductivity (VES-3); the effect will diminish at a dipping of the polluted zone into subsurface.

5.6.4. Hydrological considerations

Discharge of excess water may follow three pathways, i.e. surface runoff, shallow drainage and deep groundwater flow. At the field visit of 1985-03-28, ponding of the land was observed (*Fig.5.55*), enabling surface runoff. The small ditches surrounding the parcel were full of water at that time, indicating the occurrence of a combination of surface runoff and shallow drainage. It is hardly possible to separate the two surficial components. Surficial runoff will vary with time, not only during the seasons, but from year to year large fluctuations will occur in the amounts of water being surficially discharged from the area. Presumably, the deep groundwater flow will be relatively constant.

Groundwater heads in the main aquifer, consisting of the sand layers of the Sterksel Formation, can be estimated from groundwater isohypses. The isohypses are given in Meinardi (1984) for a wet and a dry period. The isohypses follow a regular pattern, indicating a groundwater flow from south to north at a gradient of i=1:1000. On 1982-03-15, the groundwater head at the test location had a value of M.S.L.+13.10 m. In September of the same year, the head was lower by roughly 1 m. Shallow groundwater heads were measured in boreholes on 1985-03-28. Based on these shallow heads and after estimating the level of the local reference with regard to M.S.L., shallow groundwater isohypses were composed (*Fig.5.62*). From a comparison with the heads at deeper levels, it may be concluded that the shallow heads were higher than the deeper heads at the centre of the parcel and, hence, a downward flow of groundwater occurred on

Fig.5.63. Tritium data for well C on 1983-10-01.

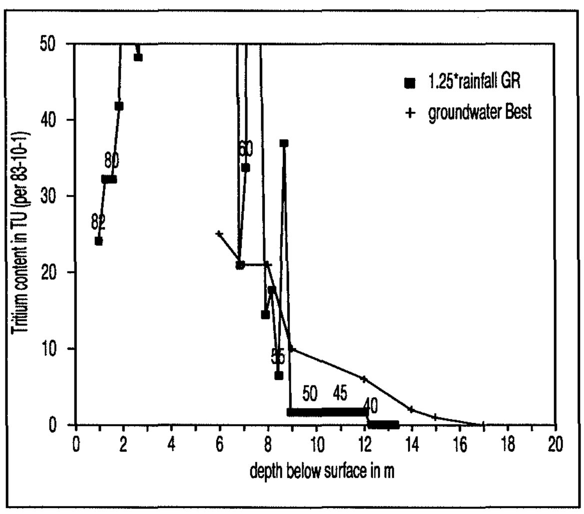


Table 5.3. Results from the shallow boreholes (concentrations in mg l^{-1}, except for pH and electrical conductivity ($mS{\cdot}m^{-1}$)

no.	Cl^-	NO_3^-	SO_4^{2-}	pH	E.C.
a -1	16	130	44	5.46	46
a -2	21	130	35	7.30	66
b	24	38	43	6.83	76
c	25	45	88	6.88	60
d	350	16	67	6.96	300
e	210	14	630	7.08	210
f	7	<1	56	6.71	96
g	60	18	88	7.37	80
h	9	2.3	81	6.77	76

Table 5.4. Results from the mini-screens in cored drilling C; observations on pH and conductivity ($mS{\cdot}m^{-1}$)

no.	depth	pH	E.C.
C3	6 m	6.7	127
C4	7 m	6.4	134
C5	8 m	6.5	163
C6	9 m	6.5	180
C7	12 m	6.9	140
C8	14 m	6.6	84
C9	15 m	7.0	96
C11	17 m	7.2	87
C12	19 m	7.2	66
C14	21 m	7.1	49
C15	22 m	7.2	49
C16	23 m	7.0	62

1985-03-28. A downward flow will most likely also prevail in other periods (see *Fig.5.63*).

The groundwater contours in the Sterksel aquifer will also represent the gradients in head in the Nuenen Group. An estimate can be made of the rate of flow in the Nuenen Group by using the horizontal permeability k_h of the sandy layers in the Nuenen Group determined from the six pumping tests, which were carried out in 1982 (Obdam, 1984):

k_h = 1.5-1.8 $m{\cdot}day^{-1}$; at a depth of roughly 7 m;
k_h = 3.7-4.8 $m{\cdot}day^{-1}$; at a depth of roughly 15 m;
k_h = 6.7-7.5 $m{\cdot}day^{-1}$; at a depth of roughly 20 m;

As the permeability increases with depth, the rate of horizontal flow will also increase with depth, the gradient in the isohypses remaining at i=1:1000.

The vertical percolation of groundwater through the Nuenen Group can be estimated from the tritium measurements. The interpretation given in *Fig.5.63* takes into account the sampling date. The downward percolation is I/p=0.286 $m{\cdot}a^{-1}$ and, hence, I=100 $mm{\cdot}a^{-1}$ for p=0.35. The multiplication factor is f=1.25, corresponding to the value of the regional effect in local precipitation. The interpretation does not show a perfect fit, as could be expected in the given situation.

5.6.5. Chemical composition of groundwater samples

The samples, analyzed with regard to the chemical composition of the groundwater, were taken on different dates. All analyses were carried out at the RIVM laboratories, implying that the results can be mutually compared. The samples were also taken from different depths. One series of samples was collected from the shallow boreholes on 1985-03-28. Another series was drawn from the observation screens and the pumping screens of the cored drillings in September 1983 and also the mini-screens of drilling C were sampled in 1983. The various results are represented in *Tables 5.3 to 5.5.* In some cases, the analyses only concerned a few parameters; in other cases, all major elements were analyzed.

Table 5.5. Average results from deeper screens; average observations; nitrate concentrations are zero, all concentrations in mg l^{-1}, except for pH and conductivity($mS{\cdot}m^{-1}$).

no.	depth	Cl^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	E.C.
B3	22 m	35	15	.03	59	6.5	21	1.2	0.7	7.1	44
B4	14 m	57	207	.0	151	17	31	1.7	2.2	6.9	80
B2	14 m	296	227	.03	327	35	43	1.5	2.3	6.8	167
B1p	14 m	389	280	.03	356	40	67	1.5	2.4	6.8	200

B2; B3; B4 represent average values over three small screens in the indicated drillings; B1p represent the highest values found in pump screen p installed in well B1.

Three different types of groundwater could be recognized from the chemical analyses of samples from the cored drillings (*Table 5.5*). Groundwater, with the highest values for all parameters (conductivity more than 100 $mS{\cdot}m^{-1}$), is supposed to have originated at a dunghill (*Fig.5.54*). An example is B2 in *Table 5.5*; the most polluted groundwater is found in B1p. Groundwater with a conductivity of less than 100 $mS{\cdot}m^{-1}$ is supposed to have been recharged in agricultural lands. High sulphate levels may indicate the application of manure slurry. Lower sulphate levels, with still relatively high concentrations of the other compounds, may have been derived from lands receiving predominantly fertilizer. The observations at drilling B3 are an example of this.

On 1985-03-28, samples from shallow boreholes (drilling h is an existing well) were taken and analyzed. The results, which are represented in *Table 5.3*, also indicate a variable origin of the groundwater. A groundwater type with low values of conductivity and of sulphate concentrations, but with high nitrate concentrations, was observed in the centre of the test location (boreholes a-1 and a-2), where clay was excavated. Similar groundwater, but with higher sulphate and lower nitrate concentrations, was present at other places with a more clayey soil. The highest conductivity value was observed at drilling d on the site of the dunghill. High values of some parameters were also observed at well e, where the cows gather before milking-time.

A third set of data was derived from mini-screens of well C (*Table 5.4*). The results confirm the conclusions drawn from the other series of data. Apparently, an upper zone is present in well C, where the groundwater was polluted, presumably by the percolate from the nearby dunghill. The deeper well screen results correspond to 'normal' groundwater. The differences in conductivity, also detected by the VES, will be used to further determine flow patterns in the subsurface of the test location. Given the density of the observations, including the VES results, a subsurface zone containing polluted water from the dunghill can be located. The flow pattern, represented by that zone, can be used to estimate horizontal and vertical flow components.

5.6.6. Horizontal and vertical flow rates

The loam layer between 1 and 3 m below surface is important with regard to the flow of groundwater. Groundwater heads above this layer were higher than below it; also the flow pattern above the loam layer deviated from the regional pattern. The sedimentological analysis indicated the large areal extent of this layer. Horizontal flow in the deeper strata of the Nuenen Group will obey Darcy's Law. The gradient in groundwater head is about i=0.001. From the pumping tests, an increase of the permeability with depth can be derived roughly according to the relation:

$$\mathbf{k_h = 0.4*z}$$

where: k_h ($m{\cdot}day^{-1}$) is the horizontal permeability; z is the depth (m) below the base of the loam layer, at a depth of 3 m.

The actual horizontal velocity of flow is:

$$\mathbf{v_x = 1/p*k_h*i = 1/p*0.4z*0.001\ (m{\cdot}day^{-1})}$$

where: p = porosity.

The vertical velocity is assumed to have a constant value:

$$\mathbf{v_z = I/p\ (m{\cdot}a^{-1})}$$

where: I is the constant downward velocity ($m{\cdot}a^{-1}$) below a depth of 3 m.

The components of the groundwater flow at a certain place (x,z) below the upper loam layer may be approached by:

$$\mathbf{v_x = dx/dt = 1/p*0.4z*0.001*365\ (m{\cdot}a^{-1})}$$

$$\mathbf{v_z = dz/dt = 1/p*I\ (m\ a^{-1})}$$

hence: $\mathbf{dx/dz = (0.4z*0.001*365)/I = 0.146*z/I}$

which is the differential equation representing a flow line. Elaboration, taking into account the appropriate boundary conditions, yields the equation for a flow line:

$$\mathbf{x = 0.073\ z^2/I}$$

Flow lines become apparent in considering the effect of pollution derived from the dunghill in drillings B1; B2; C and the VES Best-1; Best-3; Best-4; Best-8 and Best-10. Both the upper and the lower boundaries of the polluted zone represent flow lines (*Fig.5.64*), where x and z can be determined and, hence, I can be estimated. Results are represented in *Table 5.6*. The calculated values for I show some variation, probably due to the complexity of the flow. Nevertheless, the results indicate a downward infiltration, which is smaller than I=240 $mm{\cdot}a^{-1}$ (rainfall minus the estimated evapotranspiration). Yet, the average value of I=115 $mm{\cdot}a^{-1}$ corresponds to the value I=100 $mm{\cdot}a^{-1}$ determined from the tritium measurements, also implying that a value p=0.35, or even more, is a good estimate for the porosity. In the case of the test location, about 110 $mm{\cdot}a^{-1}$ will infiltrate to deeper layers. The remainder will be discharged by

Table 5.6. Values for the downward percolation I ($mm{\cdot}a^{-1}$) below the upper loam layer (base d=3 m) derived from flow patterns; (u=upper; l=lower)

	x_u m	x_l m	z_u m	z_l(m) m	I_u $mm{\cdot}a^{-1}$	I_l $mm{\cdot}a^{-1}$
B1/B2	60	80	10	12	122	131
C	20	40	4	9	60	116
Best-1	110	130	14	17	130	162
Best-3	10	30	0	1	-	-
Best-4	20	40	1	6		66
Best-8	25	45	1	7	-	79
Best-10	60	80	10	13	122	154

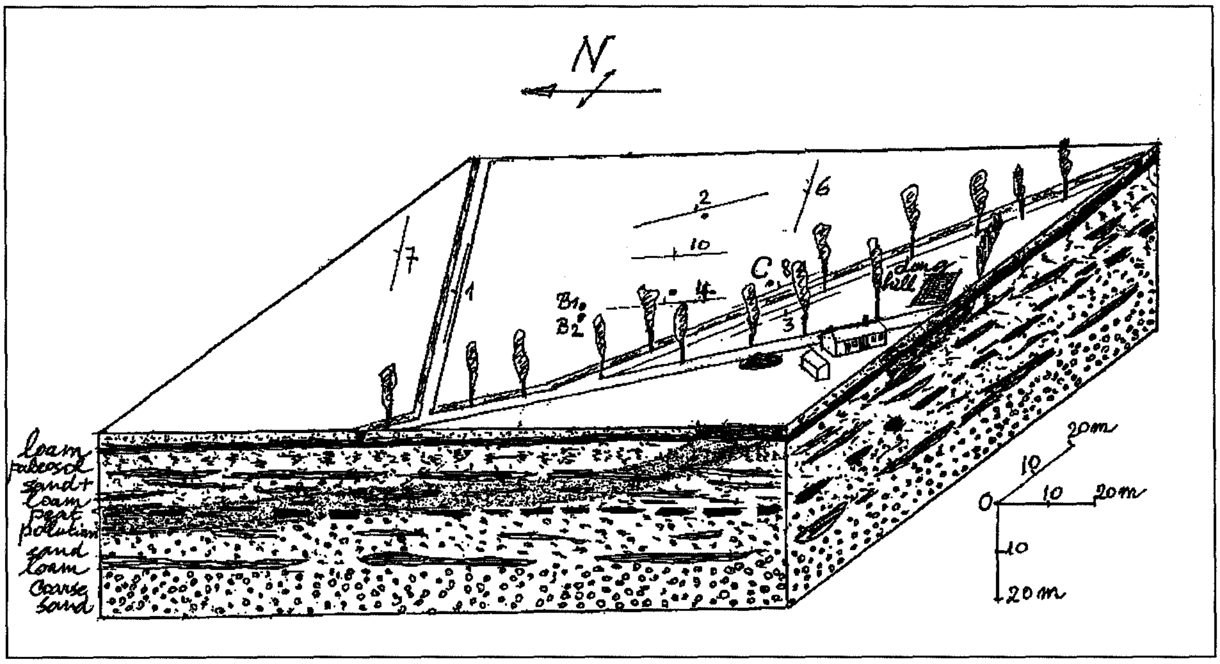
surficial flow. Above the shallow loam layer, only transport on the parcel scale will occur. For the regional transport of (polluted) groundwater, the deeper layers are more important.

5.7. Discussion and conclusions

The detailed investigations concerned two cases of soil investigations on agricultural land, two in forest areas and one near a swamp. The actual velocity of downward percolation was determined mainly on the basis of groundwater tritium levels. For a determination of the downward flow, the values determined have to be divided by the porosity. In a number of cases, the groundwater recharge calculated by means of the tritium levels could be compared to values derived by other methods. At Best, the location of a polluted plume of water made it possible to quantify the horizontal and vertical componenents of the flow. The comparison with the tritium-based vertical percolation resulted in a value for the porosity of p=0.35, or even slightly more. At Stippelberg, the situation of a transition in groundwater quality, caused by a differences in vegetation, yielded an estimate of the vertical velocity; comparison with tritium data resulted in a value for the effective porosity of p=0.35. The value of p=0.35 will be used for the interpretation of the observed tritium contents; the effective porosity will again be discussed in the concluding chapter.

The potential annual evapotranspiration of agricultural crops may be approximated by the reference evap-

Fig. 5.64. Block diagram of the Best test location, indicating in projection the effect of pollution.



otranspiration E_r, multiplied by the vegetation factors. The long-term average precipitation can be estimated. An elaboration for the Venhorst situation results in average values of P=740 mm·a^{-1} and E_p=500 mm·a^{-1}. The tritium data indicated a groundwater recharge of 290 mm·a^{-1}. The difference is due to an actual evapotranspiration which is smaller than the potential value. The observed difference of 50 mm·a^{-1} roughly corresponds to the expected value (Werkgroep HELP, 1987). The recharge to agricultural lands will be further discussed in the regional studies.

Values determined for the recharge of groundwater in forest areas varied widely, depending on the situation of open spaces and forest lanes near the observation well. For this reason, no strict conclusions can be drawn from the detailed investigations with regard to an average value of the actual forest evapotranspiration. Especially the Vredepeel investigation gave an insight in the effect of forest lanes.

It became clear from the investigations that a certain part of the forest evapotranspiration will consist of open water evaporation, presumably from rainwater intercepted by the tree canopy. The effect on the tritium level is, apart from the regional factor in rainfall, that the tritium levels in precipitation become enriched with tritium, but also with other natural isotopes. For the interpretation of tritium levels in the groundwater of forest areas, the local rainfall levels have to be multiplied by a factor of roughly f=1.5, additional to the possible regional effect.
The Griendtsveen investigation illustrated the hydrological conditions prevailing in swampy areas. The groundwater recharge determined had a relatively low value of roughly I=100 mm·a^{-1} for the nearby swampy area, where the peat had been excavated. Presumably, the low values are related to a large value of the actual evapotranspiration by phreatophytes. The groundwater tritium levels were lower than the corresponding expected rainfall levels, maybe because the evapotranspiration removed the full summer precipitation. The groundwater recharged in the remnants of the raised bog indicated the occurrence of open water evaporation, probably from the large volumes of open water in the non-excavated area.

The results of many field studies clearly indicated that local variations in the vegetation pattern have an effect on the groundwater composition, including the natural isotopes. The interpretation of the tritium profiles from Stippelberg and Vredepeel indicated that the presence of open spaces in a forest area will cause an increase in recharge and changes in the multiplication factor relating groundwater and rainfall. In interpretating tritium profiles in single wells, care should be taken with regard to the homogeneity of the recharge area, possibly causing variations in evapotranspiration.

In addition to incidental deviations between measured and expected ^{3}H levels in groundwater, it seems that there is a systematic deviation with regard to the peak values in rainfall observed in the years 1963-1965. The values observed in Vredepeel and Griendtsveen groundwater, estimatedly recharged in 1962-1965, are systematically lower than would be expected on the basis of rainfall ^{3}H levels. A possible explanation is that the Vienna figures from those years cannot be extrapolated to the Netherlands.

The hydrological considerations, based on the sedimentological analysis of the soil at the Best test location, supported the determination of a downward flow estimated from the tritium levels in groundwater. The vertical component of flow was calculated at roughly I=110 mm·a^{-1}. A large part of the average rainfall excess, which is in the order of 250 mm·a^{-1}, will be discharged by surficial components on the parcel scale. A quantitative extrapolation of the Best data is not easily done but, in general, it may be stated that in cases where a less pervious layer of great areal extent is present at a shallow depth, the hydrological situation may lead to a significant surficial discharge of rainfall. The travel times in saturated groundwater will be large.

6. RESULTS OF REGIONAL INVESTIGATIONS

6.1. General

Travel times of groundwater in the (shallow) subsurface are a function of recharge and the geohydrological structure of the local aquifer system. The elements composing this structure are characterized by a relatively strong local variation, implying that also for the travel times of groundwater a large variation may be assumed. Although the measured tritium data can be interpreted in the sense of travel times, the available data is too scarce to justify regional mapping. The regional reviews of the sandy areas in the Netherlands have to focus on the values of groundwater recharge, which can be linked to topographical and meteorological factors. Investigated regions are the four major sand districts and the coastal dunes. The factors determining the amount of recharge are investigated by means of local travel time determinations in the same way as was discussed for the detailed field studies. The geohydrological structure is schematized on a regional basis. Data on groundwater recharge and on the geohydrological structure are combined in a final chapter to arrive at a spatial representation of groundwater travel times.

Three elements are used with regard to the regional and long-term values of groundwater recharge in agricultural areas:

- Regional water balances, composed in the framework of regional studies of the Netherlands groundwater situation and aiming at the extraction of groundwater for the public water supply.
- The consideration of tritium profiles, determined at detailed hydrological investigations of 10 test farms of the National Fertilizer Institute.
- The interpretation of the tritium levels in samples drawn from the screens of the National and Provincial Groundwater Monitoring Networks (LMG and PMG).

A discussion on groundwater in areas covered with a natural vegetation is based on:

- Studies on the quantity and quality of groundwater recharge in the Veluwe area;
- Eight detailed tritium profiles from groundwater in the coastal dunes near Monster.

All the methods have their specific drawbacks. The regional water balances consist of a comparison of hydrological parameters, which, in general, cannot be determined very accurately. Hence, also the resulting determination of groundwater recharge will be inaccurate. The tritium profiles measured at the test farms show a high degree of accuracy and the local hydrological situation was thoroughly investigated. However, the extrapolation of the results of the detailed studies to the whole of the sandy regions in the Netherlands will pose problems. An interpretation of the tritium content, measured in samples from the large number of monitoring wells, does not always result in an accurate determination of travel times, because per well only two, and in a few cases three, values are determined. Nevertheless, in combining the results and in comparing them to the variation in the average rainfall excess, as discussed in Chapter 3, it is possible to present a regional review of the average groundwater recharge in the sandy regions.

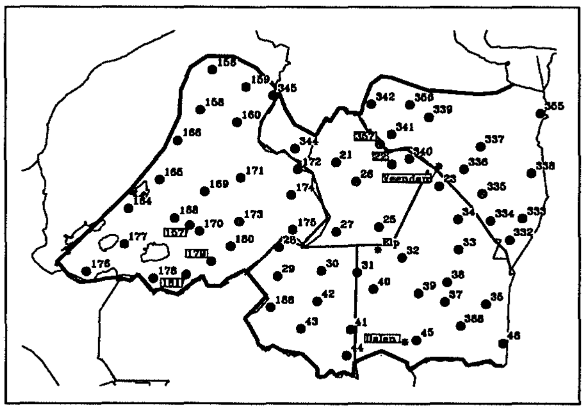
6.2. The northern sand district

6.2.1. Geography and landscape

The northern sand district (*Fig.6.1*) occupies the whole province of Drenthe and the eastern parts of the provinces of Groningen and Friesland, where the soil is predominantly sandy. Based on differences in landscape, a number of subregions may be distinguished:

1. East Groningen
   Large parts of the south-east region of the province of Groningen were covered by a vast raised

Fig.6.1. The northern sand district; location of LMG wells and the investigated farms.



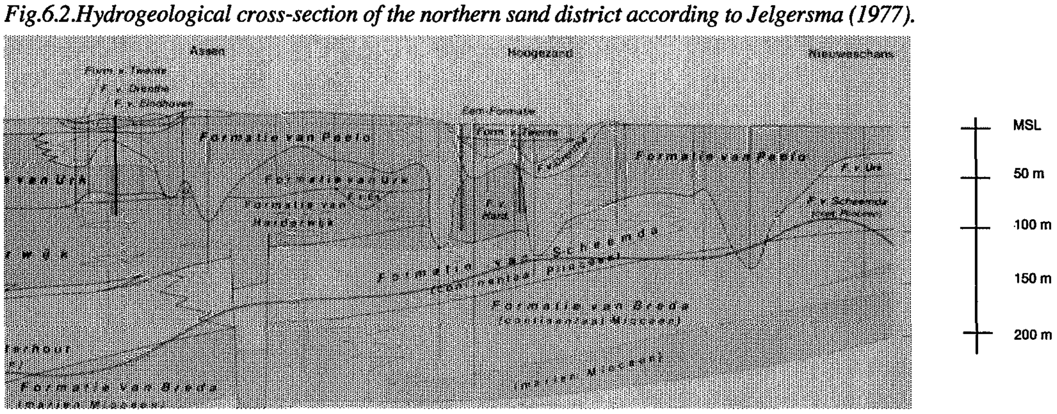
bog up to a few centuries ago. After extraction of the peat, the land was reclaimed and turned into an important agricultural area. At present, the cultivation of potatoes, varied with other crops, represents the main land use. The drainage of excess water is provided by a dense system of canals and ditches. The most eastern subregion, called Westerwolde, is an old agricultural area drained by natural streams. Westerwolde never was inaccessible because of swampy conditions.

2. Drenthe
   Until the beginning of the present century, most of the province of Drenthe was covered by vast heathlands. Only near the dispersed villages had patches of arable land been reclaimed. Broad stream valleys consisted of wetlands with a swamp vegetation where peat layers could develop. But even in the heathlands, the shallow soil contains a less pervious boulder clay layer, preventing subsurface discharge. Formerly, this implied wet conditions in the winter period. At present, the drainage conditions are improved by the digging of deep ditches and the installation of tile drainage systems. The south-east part of the province was covered by a vast peat blanket. The peat has been extracted until recently. The reclaimed land was turned into arable agricultural parcels. After the introduction of fertilizer, the heathlands in the whole province were reclaimed, such that the major land use now is permanent pasture. However, a large area in Drenthe is still covered by dispersed pine forests.
3. Friese Wouden
   The east part of the province of Friesland is the west fringe of the Drenthe highlands. Due to the downstream situation and the lower altitude of this subregion, the development of peat in the upper soil layers was more important. The land consisted of broad valleys with a peat cover, alternating with low sandy ridges. After excavation of the peat and the reclamation of the former wastelands, made possible by the introduction of fertilizer, the Friese Wouden became an agricultural area important for animal husbandry. The drainage was improved. Small pine forests are present in various parts of the Friese Wouden. The whole southern part of the province consists of a vast end moraine, present at land surface in the Gaasterland region, but also present as sandy layers at shallow depths in the rest of the subregion.

6.2.2. Hydrogeological situation

The subsurface of the northern sand district originally consisted of the flat fluvial plain, mainly of the River Rhine, which, however, was thoroughly remaniated by glacial phenomena during the Pleistocene Age. During the passage of glaciers, deep and broad valleys were scoured, either by the ice, or by melt water. The filling of the valleys consisted mostly of fine material belonging to the Formations of Peelo and Drenthe (in geological terms). In huge basins, the Peelo Formation has developed as so-called potclay, which is practically impervious; but in other areas, the formation consists of sandy sediments, constituting an upper aquifer of a low transmissivity. Underneath the fluvio-periglacial sediments a deeper aquifer is usually present, consisting of permeable Pleistocene and Upper Tertiary formations (the Miocene and Pliocene layers in *Fig.6.2*). Deeper clay layers, also of a Tertiary origin, constitute the virtually impervious base of the surficial aquifer system. The Tertiary layers are situated at a relatively shallow depth in the east, implying that the transmissivity of the subsurface decreases in the same direction. Another aspect of the glacial periods is the deposition of a ground moraine over large parts of the area. Where the ground moraine is lacking, often less pervious river loams confine the subsurface aquifer systems. Shallow less pervious soils hinder the groundwater recharge of the deeper subsurface. The structure of the aquifer system is given by Jelgersma (1977).

Fig.6.2.Hydrogeological cross-section of the northern sand district according to Jelgersma (1977).



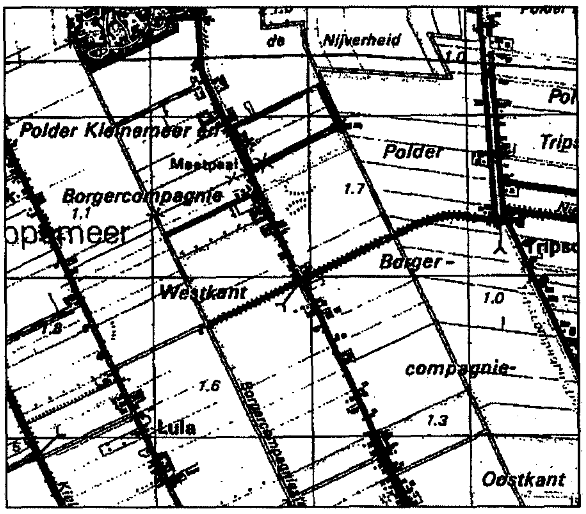
The long-term water balance of the province of Drenthe was investigated by RID (1967) and by the Werkgroep Reg. Ond. Drenthe (1978, Drenthe Regional Working Group). The following magnitudes of the terms, which represent regional averages, can be derived:

Precipitation (period 1953-1968)	812 mm·a^{-1};
Evapotranspiration (1931-1960)	477 mm.a^{-1};
Rainfall excess	335 mm·a^{-1};
Surficial runoff over boulder clay	45 mm.a^{-1};
Percolation to the shallow subsurface	290 mm·a^{-1};
Discharge via shallow layers	230 mm.a^{-1};
Recharge of deeper aquifers	60 mm·a^{-1};

The above figures represent provincial averages; it may be assumed that in more elevated areas, where the groundwater recharge is usually more than the average recharge, the surficial discharge components will be smaller.

The hydrological situation of the province of Groningen is described in (Cramer et al., 1979), including a general water balance. The water balance contains a determination of the average precipitation, P= 800 mm·a^{-1} , and an estimate of the actual evapotranspiration, E= 485 mm·a^{-1}, which is based on the comparison between incoming and outgoing water flows. The authors noted that the accuracy of the estimate will be low.
For the province of Friesland no general water balance data are available. The geohydrological structure is given in the Grondwater Kaart van Nederland, i.e. the Netherlands groundwater map, composed by (DGV-TNO).

Fig.6.3. Situation of the Veendam test farm.



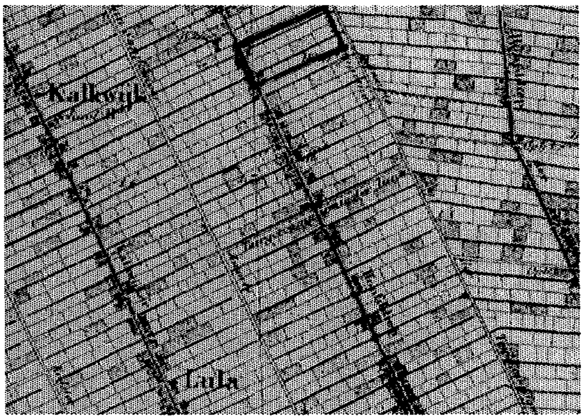


Fig.6.4. Topographical map of 1850.

6.2.3. The Veendam test farm

6.2.3.1. Situation and investigations

The Veendam test farm is located in a hamlet, Borgercompagnie (*Fig.6.3*), in a region called the Langeleegte, which is part of the Groningen Veenkolonien (peat colonies). During the Holocene Age, a large raised bog, used for peat digging as early as the Middle Ages, had developed. A large scale extraction by private companies started in the 17th century. The bog was drained via a system of parallel canals (diepen) and ditches (wijken); this system was also used to ship the turf. The peat layers in the area of the test farm were excavated around the year 1650; the root zone was reworked into the remaining sandy soil, leaving an agricultural area with a sandy soil rich in organic elements. Already in 1850, the landscape had taken on its present form (*Fig.6.4*).

After excavation of the peat, an older landscape appeared, consisting of brooklands and cover sand ridges, implying small variations in land elevation and different soils. The geological genesis of the sandy layers is dominated by the presence of a former glacial valley, which is now the broad Hunze valley. The valley, filled in by fine sediments, has its base at a depth of 35 m, where loamy layers are present. These base layers may also contain brackish groundwater. The upper sand layers belong to the Twente Formation with fluviatile and eolian deposits. At a depth of roughly 10 m, layers belonging to the Eemian formation may be present, which contain peaty components. Below these layers, fluvio-periglacial sediments belong to the Peelo Formation, which rest on even finer sediments.

The investigations focussed on the parcels near the farmyard (*Fig.6.5*). A Stiboka survey was based on 62 boreholes. The hydrological investigations consisted

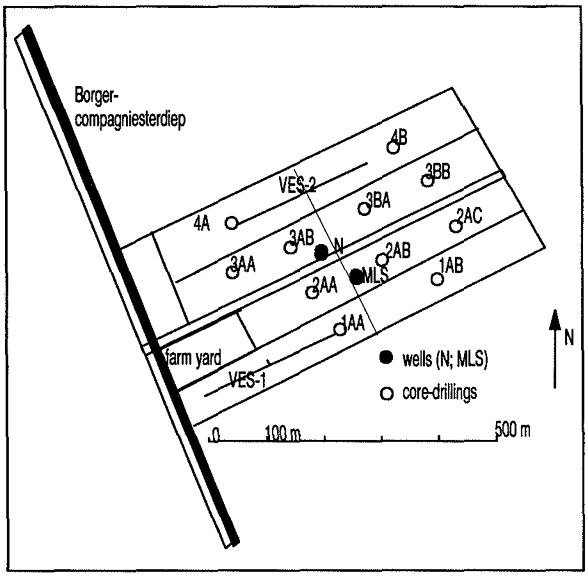


Fig.6.5. The investigations at the Veendam farm.

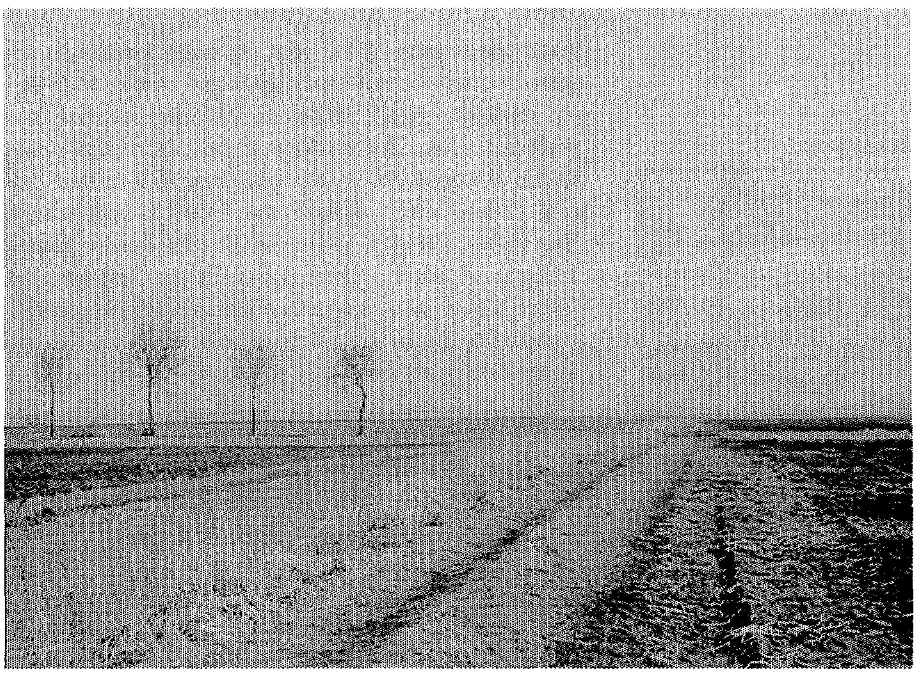
of two VES, a coverage by EM-31 measurements and the drilling of 11 cored drillings to a depth of 8 m, in which observation screens were installed. A cable-tool drilling (N well) was drilled to a depth of 15 m and provided with screens. Samples were taken, water levels measured and the wells surveyed. A multi-layer sampler arrangement was installed and used.

The structure of the land is largely determined by the system of parallel canals and ditches. Elongated rural centres developed along the central canals, housing the farmyards. Near the farm, the central canal has been degradated to a broad draining ditch. The boundary of the farmland consists of a road parallel to the canal and marking the border of the former concession. The land is flat and empty with not many trees. Because of the regular infrastructural elements and the scarcity of trees, the landscape gives the impression of a desolated land (*Fig.6.6*). The image of uniformity is enforced by the widespread cultivation of potatoes. Potatoes also used to be grown on the test farm, but at present the land is laid in pasture; many neighbouring farms are still used as arable land.

6.2.3.2. Geohydrological structure

A sedimentological analysis of the cored drillings resulted in a description of the shallow subsurface of the farm. The layers consisted of fine silty material, which showed but a few structures after preparation. One conclusion was that, also in the upper 3 m of the sandy layers, plant roots and other organic material were present, indicating vegetation horizons within the Upper Pleistocene deposits. The total of the investigated layers to a depth of 8 m belong to the Twente Formation, alternately deposited by streams and by the wind. Also the VES (*Figs.6.7* and *6.8*) indicate a predominantly sandy character of the layers to a depth of 35 m below surface. Given the relatively high resistance of the base layer, it has to consist of loamy layers of a considerable thickness. At a depth of approximately 13 m below surface, the resistivity of the sand layers increases; this is caused by groundwater with a lower conductivity in the layers concerned.

Fig.6.6. The Langeleegte near Borgercompagnie.



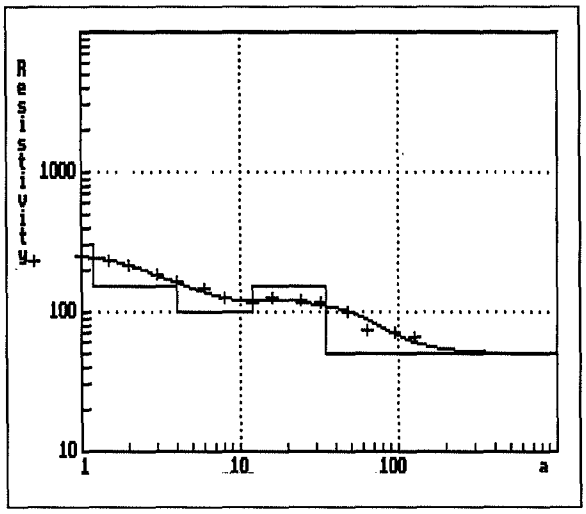


Fig.6.7. VES Veendam-1.

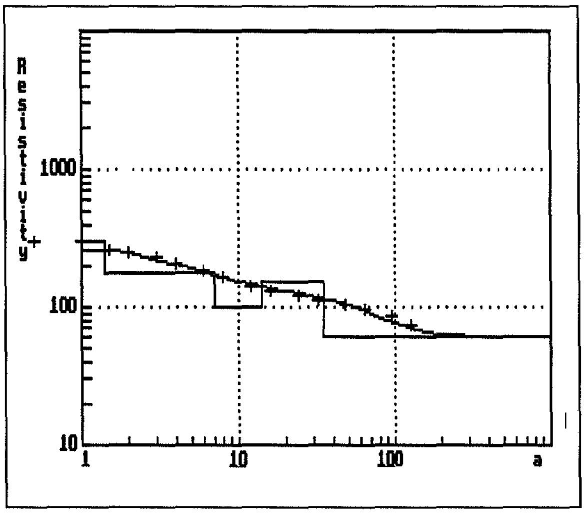


Fig.6.8. VES Veendam-2.

The measured EM-31 values (*Fig.6.9*) do not indicate large differences; most values vary between 3 and 6 $mS \cdot m^{-1}$. The variation may be the result of differences in the thickness of the unsaturated zone and the corresponding more-or-less sandy soil, indicating the remnants of cover sand ridges and the lower basins in between. Only near the ditch, at the southeast boundary of the parcel, were higher EM-31 values observed; this may have several reasons. Additional information would be required for a further explanation of this phenomenon. High values near the farmyard may be the result of polluted groundwater recharged in the yard. The structure of the subsurface has been summarized in *Fig.6.10.* Most probably, the whole subsurface to a depth of 35 m consists of one single aquifer.

The water levels measured in the cored drillings have been related to a local reference level in order to compose groundwater isohypses. From the isohypses (*Fig.6.11*) follows that the groundwater flows to the north-east at a gradient of approximately 1:3000, which corresponds to the regional trend as indicated by DGV-TNO (Groundwater Map). A conclusion is that the horizontal flow will be small because both the hydraulic gradient and the transmissivity are small.

Tritium contents were determined in samples from mini-screens in the cable-tool drilling. The interpretation of the measured tritium profile (*Fig.6.12*), assuming that D=35 m, resulted in:

f=1.0 (regional factor);

I/p=0.90 $m \cdot a^{-1}$ and I= 315 $mm \cdot a^{-1}$ at p=0.35.

The regional factor corresponds to the expected value in rainfall of f=1.02. The value of the downward percolation represents the average local groundwater re-

Fig.6.9. EM-31 values ($mS \cdot m^{-1}$).

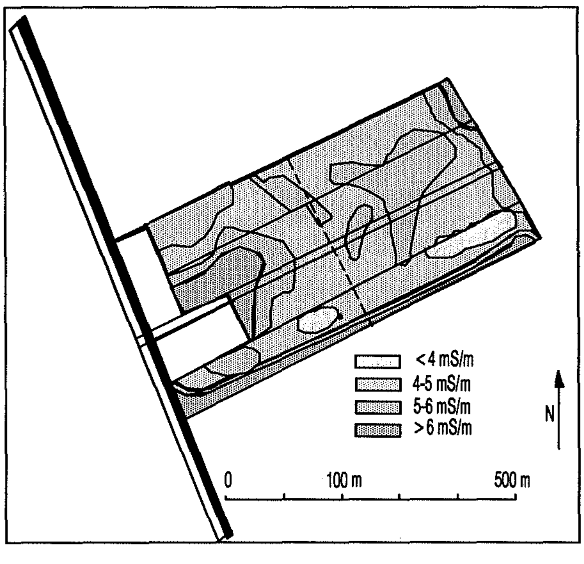
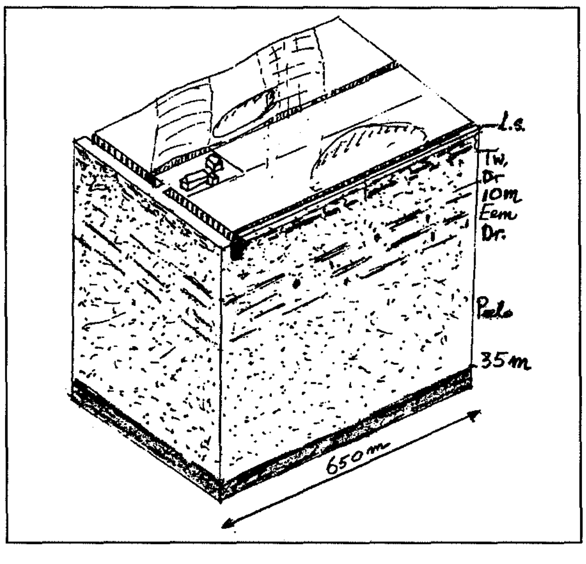


Fig.6.10. Soil structure.



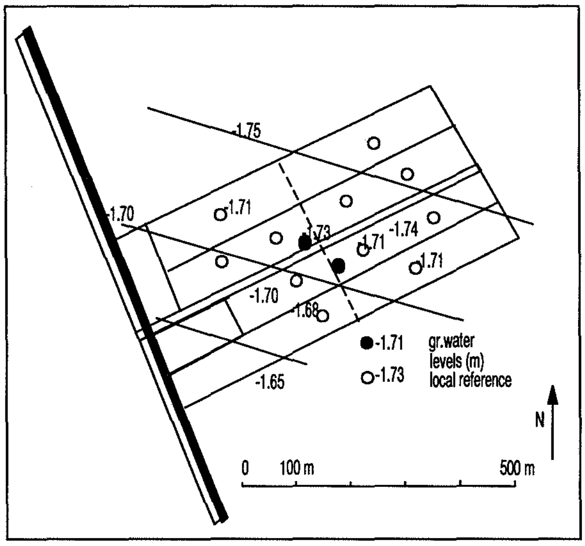


Fig.6.11. Isohypses on 870408.

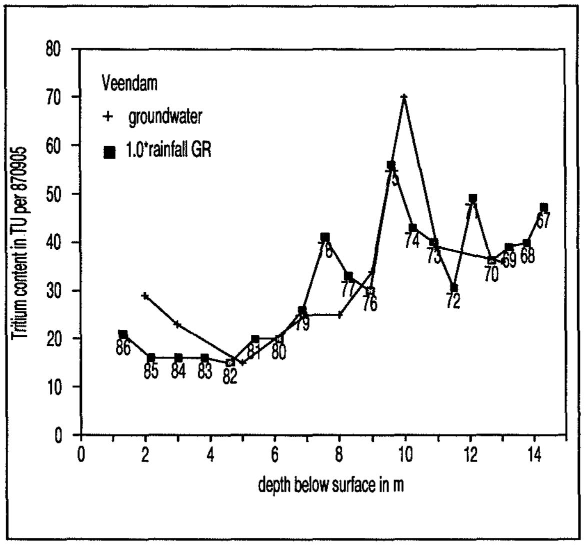


Fig.6.12. ^3H contents N well.

charge, which may be compared to the local values of precipitation and the potential evapotranspiration.

6.2.3.3. *Environmental implications*

The average annual application of nitrogen compounds to the farmland of the Veendam test farm in the period before the investigations was 740 kg·ha^{-1}, divided in 470 kg·ha^{-1} as fertilizer; 170 kg·ha^{-1} as manure slurry and 100 kg·ha^{-1} as field manure. The hydrological situation indicates a downward percolation of the rainfall excess, transporting the excess nitrogen compounds. The nitrate concentrations in the uppermost saturated groundwater, taken from the screens of the shallow boreholes, are represented in *Fig.6.13*. The average concentration of nitrate in the upper groundwater is 17 mg·l^{-1} (as N), representing a total of 60 observations. At a groundwater recharge of 315 mm·a^{-1}, as estimated from the tritium profile, it can be calculated that the average annual load at the phreatic level is 54 kg·ha^{-1}, which represents 8% of the total load. The leaching of nitrogen compounds towards the saturated zone may also be estimated from theoretical concepts, as proposed by Kolenbrander (1981) or Van Drecht (1991, the NLOAD concept). Applying the NLOAD model, the leaching of nitrogen compounds in the Veendam situation can be predicted being 19% of the total application. Hence, the observed leaching of nitrogen compounds is less than the leaching predicted with the NLOAD model; presumably, the explanation lies in the high

Fig.6.13. N content (as N in mg·l^{-1}) in shallow groundwater.

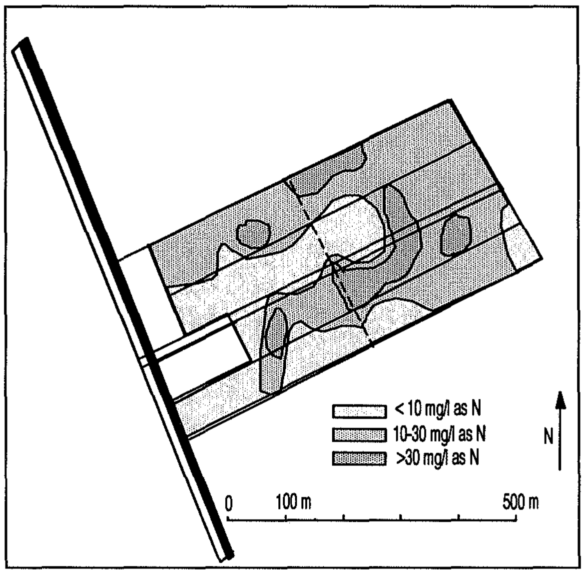
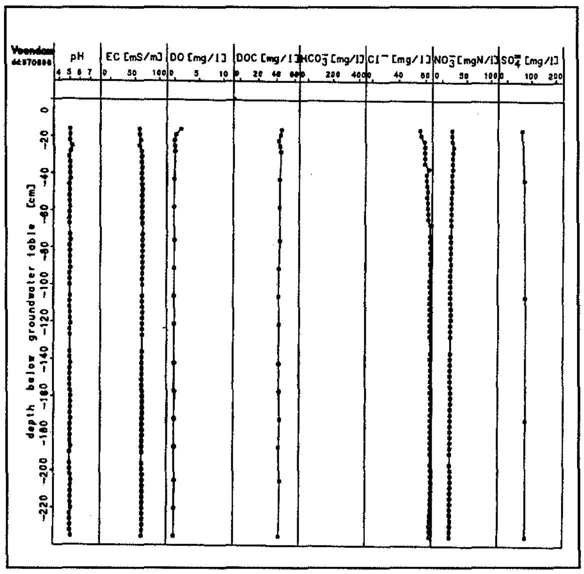


Fig.6.14. MLS results 870408.



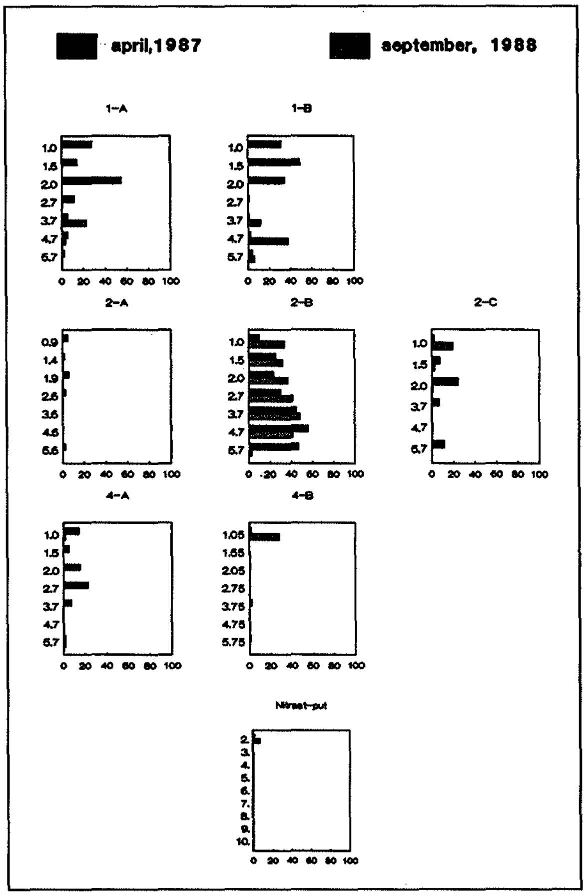


Fig.6.15. N content (as N in mg·l⁻¹) in the groundwater of deeper drillings.

organic matter content of the topsoil, hindering the formation of nitrate.

The multi-layer sampler observations are shown in *Fig.6.14*, indicating almost no fluctuations in measured concentrations versus depth. The concentrations correspond to the average values measured in the nearby groundwater. The tritium profile indicates that the observed values (covering a zone of 2 m) represent a groundwater recharge for approximately 2 years. Most evidently, the load of nitrogen compounds on the land surface was not the same in every season. It may be concluded that a mixing of water with solutes has occurred in the unsaturated zone, it has at least the form of mixing on a yearly basis.

The observed nitrate concentrations in samples from deeper screens have been indicated in *Fig.6.15*. Clearly, in the samples from some of the screens in the deeper observation wells, the nitrate concentrations have been reduced to almost zero, although the tritium profile measured in the N well indicates that also the deeper groundwater is of a relatively recent date. Based on hydrological considerations, the point of recharge and the groundwater travel times may be estimated. In comparing the nitrate concentrations in the uppermost saturated groundwater to the corresponding values in deeper groundwater, the reduction rate may be estimated. Considering the deeper values, it may be concluded that:

20% of the deep observations correspond to shallow values;
20% of the observations indicate a reduction of approximately 50%;
40% of the observations indicate a reduction of more than 80%;
20% of the observations originate in areas with a low N content in the upper zone.

The general conclusion is that the additional nitrate reduction in groundwater in the saturated zone is roughly 50%.

6.2.4. The Elp test farm

6.2.4.1. Situation and investigations

The test farm (*Fig.6.16*) is situated between the villages of Elp and Zwiggelte in the Ellertsveld, a region in the province of Drenthe. Up to 100 years ago, the Ellertsveld consisted of vast heathlands, where a few patches of land (called 'essen' and 'kampen') near the villages had been reclaimed for agriculture. Fertilization of the arable land was done with the manure of sheep and cattle, which grazed in the wastelands. The heathlands were dissected by broad brook valleys, in which meadows ('madelanden') provided hay for the winter periods. The heathlands were hardly drained by surface water, implying dry conditions in the summer and relatively wet conditions in the winter periods. The brook valleys consisted originally of marshy areas and had to be drained by a system of many small ditches. The 1850 topographical map (*Fig.6.17*) represents the situation as it used to be, clearly indicating the stream valley of the Westerborkerstroom.

The Stiboka (1988) survey indicated the differences in the topsoil conditions. On the east side of the parcel, boulder clay layers were observed, whereas in the brook valley peaty soils have developed. A zone exists at the transition between the two soil types, where the boulder clay has been eroded by the former fluvio-glacial valley, but where hardly any peat or fine stream sediments have been deposited. As a consequence, less pervious layers are absent in the topsoil of that zone. The general features of the deeper subsurface are formed by the presence of fluvio-periglacial sediments, belonging to either the Formations of Peelo, or

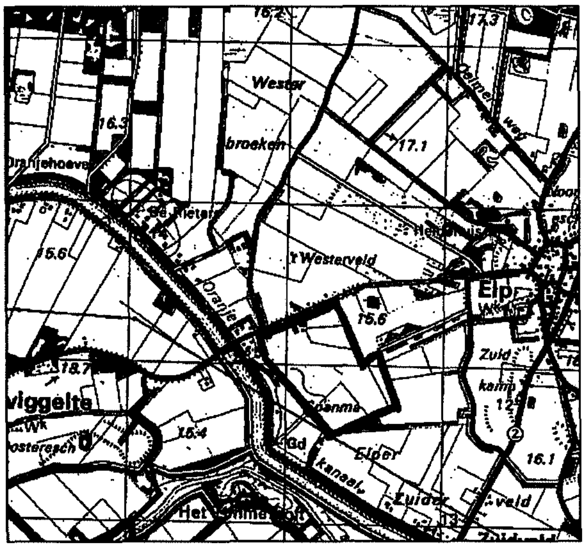


Fig.6.16. Situation of the Elp test farm.

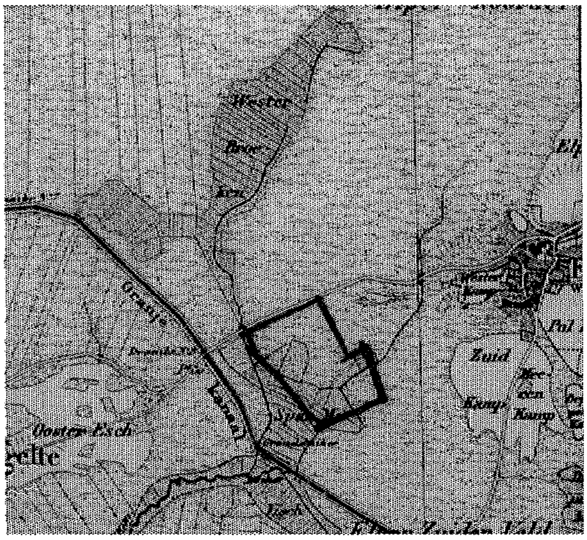


Fig.6.17. Topographical map of 1850.

of Drenthe, to a depth of some 30 m. At still greater depths, the undisturbed older Pleistocene formations of Urk and Harderwijk, resting on loamy layers of an early Pleistocene or Tertiary Age, may be found.

The investigations in the farmland (*Fig.6.18*) consisted of a soil survey based on 124 boreholes (Stiboka, 1988). The deeper soil was investigated by means of four VES, a full coverage by EM-31 measurements, the drilling of 10 cored drillings to a depth of 8 m, in which observation screens were installed, and the execution of a cable-tool drilling (N well). Samples were taken, water levels measured and the wells surveyed.

The present farmland partly occupies the former meadows and partly the old heathlands. In a relatively recent land reclamation project, the whole parcel of the farm has been divided in large fields where, at first sight, not many differences (*Fig.6.19*) exist between the two types of land. In the old wetlands a system of tile drainage has been installed and the old heathlands are drained by a widely spaced system of deep ditches. Yet, the old situation becomes apparent from different soils and also from small differences in land elevation. Some variation in the landscape was introduced by the planting of tree lanes.

6.2.4.2. Geohydrological structure

The cored drillings indicated the presence of fluvio-periglacial sediments, which were predominantly deposited in an aquatic environment. The layers from 4 to 7 m below surface consisted of uniform fine sand, where eolian deposition has also been important. The layers above a depth of 4 m contain plant residues and other humic material. The top layers of the subsurface could not be sampled by the cored boreholes. Hence, no boulder clay, peaty deposits or Upper Pleistocene cover sands were described by the sedimentological analysis, although those sediments certainly are present in the topsoil of the test farm, as it was indicated by the Stiboka survey (1988).

The subsurface was investigated by means of four VES, which showed large differences. The interpretation is shown in *Figs.6.20* to *6.23*. The upper layers represent the unsaturated zone, which consists of peat layers in VES-4 and of sandy deposits in the other VES. VES-1 is the only case were a layer of boulder clay has been interpreted. Further differences result from the presence of a loamy layer at a depth of approximately 10 m, present in the western VES and absent in the eastern part of the parcel.

Fig.6.18. The investigations on the farm.

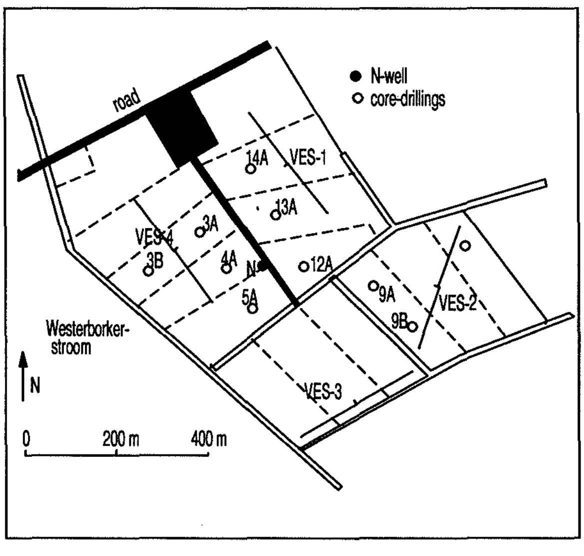


Fig.6.19. The landscape at the Elp test farm.

Fig.6.20. VES Elp-1.

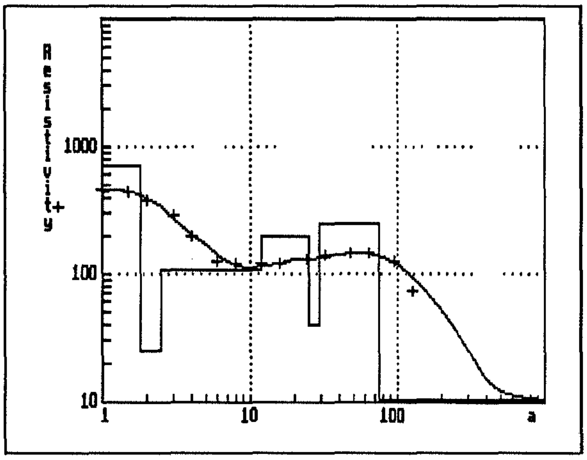


Fig.6.21. VES Elp-2.

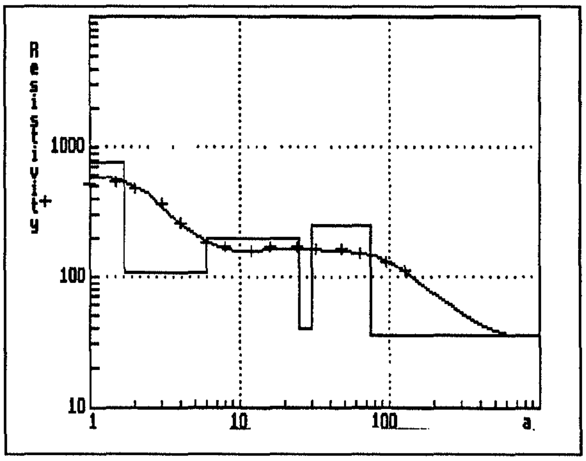


Fig.6.22. VES Elp-3.

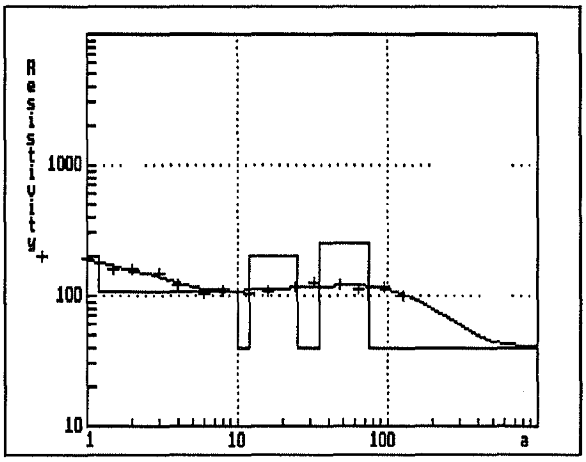
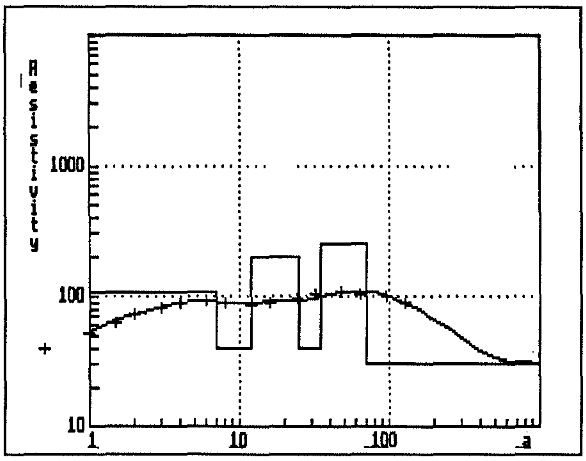


Fig.6.23. VES Elp-4.



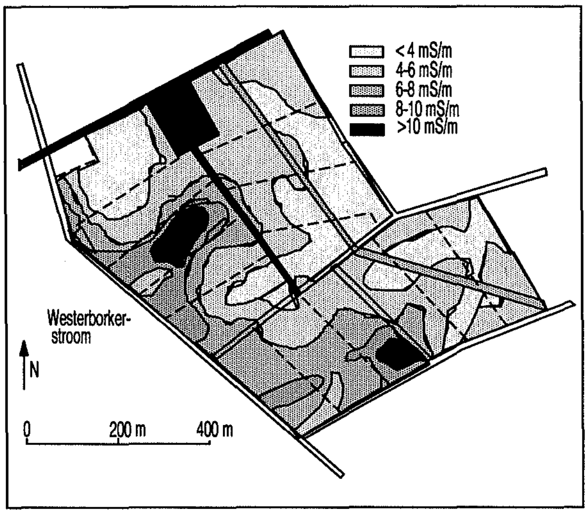


Fig.6.24. EM-31 values (mS·m^{-1}).

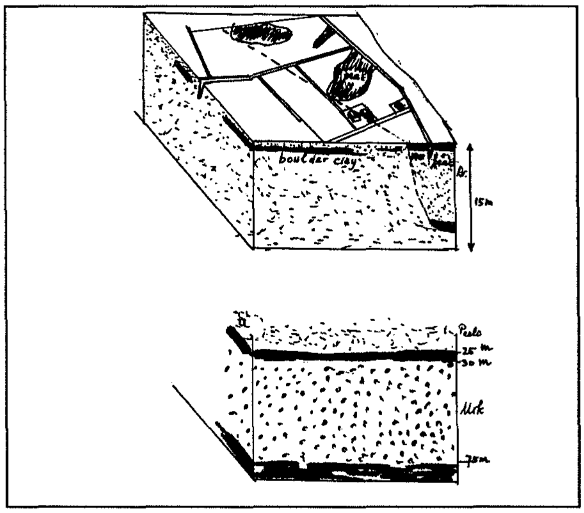


Fig.6.25. Soil structure.

The structure of the shallow subsurface can also be derived from the results of the EM-31 measurements (*Fig.6.24*). A remarkable feature is the regular strip with relatively high EM-31 values in the eastern part of the parcel. The increased values are caused by a buried pipe for the transport of natural gas, bringing gas from the gasfields in the north to consumers in the rest of the country. The areas with peaty soils, and a shallow groundwater table, can be distinguished by EM-31 values higher than 6 mS·m^{-1}. The highest values of more than 8 mS·m^{-1} indicate the zones with very shallow groundwater tables (GT II). The areas where the EM-31 values are between 4 and 6 mS·m^{-1} probably are the areas with an intercalated boulder clay layer. At places where the EM-31 values are lower than 4 mS·m^{-1}, the shallow subsurface will be completely sandy.

Presumably, the loam layer observed at a depth of 10 m forms the basis of a former glacial valley, which was present in the western part of the parcel. The valley is interbedded in older fluvio-periglacial deposits, which have their base at a depth of 25 m, where again loamy layers are present. The deeper glacial layers are present below the full parcel. Below this glacial sediment, a deeper sandy subaquifer was deposited to a depth of 75 m, where it rests on thick loamy layers, presumably of a Tertiary age and behaving as the hydraulic base of the aquifer system above it. As it may be assumed that the loam layers at a depth of 25 m will exert a limited hydraulic resistance, the whole system to the depth of 75 m will act as one single, but locally semi-confined aquifer. The geohydrological structure of the subsurface has been summarized in *Fig.6.25*.

The water levels measured on two different dates in the cored drillings were related to a local reference level in order to compose groundwater isohypses. From the isohypses on 19870629 (*Fig.6.26*), it may be derived that at least the shallow groundwater flows to the ditches within and around the parcel. The isohypses observed on 19860909 show the same tendency, but the gradients in the groundwater contours are smaller, indicating that the flow depends mainly on local factors. It does not represent a regional groundwater flow.

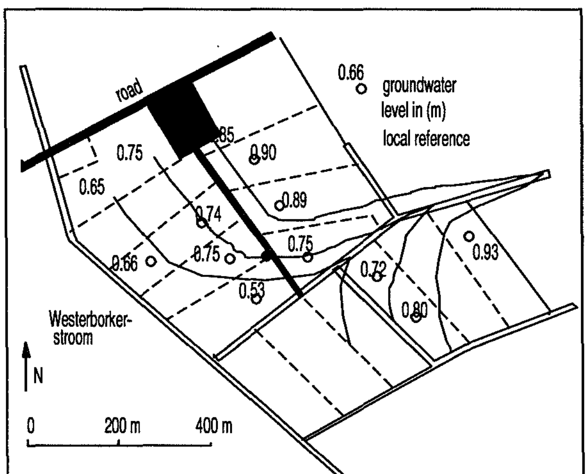
Tritium contents were determined in samples from the mini-screens of the cable-tool drilling. The interpretation of the tritium profile (*Fig.6.27*), assuming that D=75 m, resulted in:

f=1.10 (regional factor);

I/p=0.91 m·a^{-1} and I= 320 mm·a^{-1} at p=0.35.

The regional factor is slightly more than expected (f=1.05). The value of the downward percolation is

Fig. 6.26 Isohypses on 870629



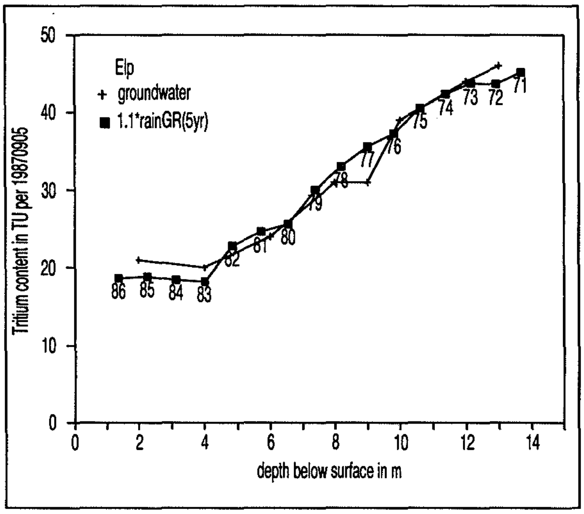


Fig.6.27. ^3H content in the N well

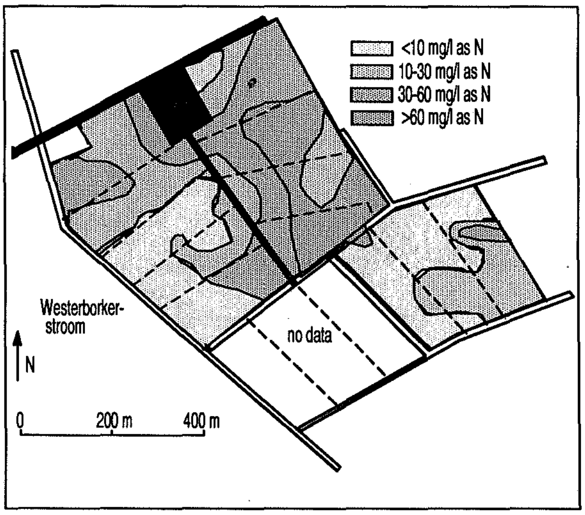


Fig.6.28. N concentrations in shallow groundwater (in $mg{\cdot}l^{-1}$ as N).

related to the value of the average local groundwater recharge.

6.2.4.3. Environmental implications

The nitrate concentrations in the uppermost saturated zone, taken from the screens of the shallow boreholes, are presented in *Fig.6.28.* The large variation corresponds to differences in soil types and in groundwater depths, being present on the farm. In general, the pattern in the nitrate concentrations corresponds to the pattern in EM-31 values (*Fig.6.24*), as could be expected. The average annual application of nitrogen compounds to the farmland, in the period before 1986, was 655 $kg{\cdot}ha^{-1}$, with 430 $kg{\cdot}ha^{-1}$ as fertilizer; 130 $kg{\cdot}ha^{-1}$ as manure slurry and 95 $kg{\cdot}ha^{-1}$ as field manure. The percolation of rainfall excess transports excess nitrogen compounds to the deeper groundwater. The average concentration of nitrate in the upper groundwater is 32 $mg{\cdot}l^{-1}$ (as N), representing a total of 111 observations. At a groundwater recharge of 320 $mm{\cdot}a^{-1}$, as estimated from the tritium profile, the average annual leaching can be calculated at 105 $kg{\cdot}ha^{-1}$, representing 16% of the total load. The leaching of nitrogen compounds predicted by the NLOAD model constitutes 12% of the total load. The observed leaching of nitrogen compounds is more than the predicted leaching.

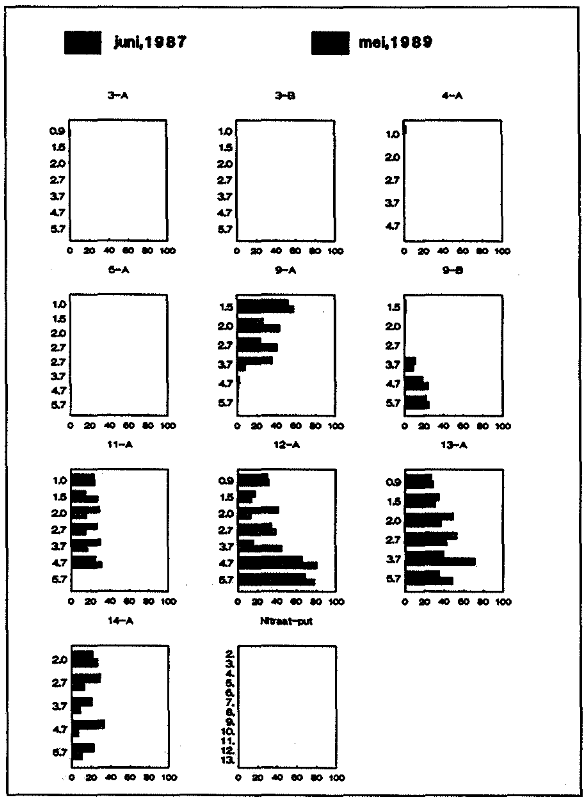
No multi-layer sampler observations were carried out. The observed nitrate concentrations in deeper screens are indicated in *Fig.6.29.* Based on hydrological considerations, the point of recharge and the groundwater travel times may be estimated. In comparing the nitrate concentrations in the uppermost groundwater to the corresponding values in deeper groundwater, the reduction rate can be estimated. It may be concluded that:

15% of the deep observations correspond to shallow values;

25% of the observations indicate a reduction of approximately 50%;

20% of the observations indicate a reduction of more than 80%;

Fig.6.29. N concentrations in deeper groundwater (in $mg{\cdot}l^{-1}$ as N) of the Elp farm.



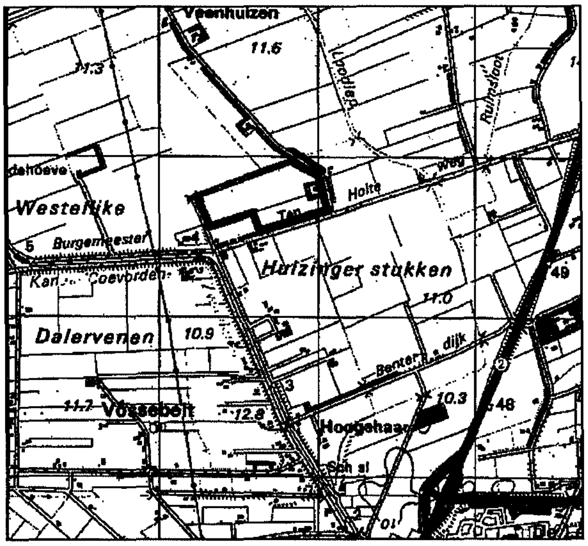


Fig.6.30. Situation of the Dalen test farm.

40% of the values originate at areas with a low N content in the upper zone.

The reduction rate in groundwater of the saturated zone is roughly 50%.

6.2.5. The Dalen test farm

6.2.5.1. Situation and investigations

The medieval overland route from the northern marine clay belt to more southern regions passed by the old village of Dalen. Dalen is situated between two brooks, the 'Droste diep' and the 'Loodiep', confluencing at the town of Coevorden. The structure of the village consisted of a central area with arable fields in the form of essen and kampen on the higher grounds and hay fields and meadows in the valley of the Droste diep. The test farm (*Fig.6.30*) is situated in the broad valley of the Loodiep, which probably was too far away from the village to be parcelled in meadows. Yet, the 1850 topographical map (*Fig.6.31*) indicated land divides and a denomination of the area; in 1875, the land was already grassland. A few hundred metres west of the farm, the 'Westelijke Daaler Venen', originally a raised bog with a peat cover, have been reclaimed.

The general soil structure of the Dalen farmland is strongly related to its situation in the outer fringes of the Loodiep valley. In the shallow soil, peat layers are present, as well as boulder clay and river loam. But a zone with a completely sandy topsoil is also present. The location of the Loodiep was determined by a system of glacial gullies, later filled in with fine sandy and loamy material. The stream has partly eroded the boulder clay cover and, locally, it has deposited river loams. The base of the fluvio-glacial valleys probably was situated at a depth of approximately 25 m (ter Wee, 1979), where a coherent system of loam layers is present. Below the glacial valley system again a sandy layer is found down to a depth of roughly 60 m below surface, which probably belongs to the Urk Formation of a Middle Pleistocene age. The deeper sandy layers rest on a complex of loamy layers, which are probably of an Upper Tertiary age and belong to the Scheemda Formation. Presumably, the loam layers at the base of the glacial valley system will not behave as a completely confining layer, but the Tertiary layers certainly will.

The investigations on the farm (*Fig.6.32*) consisted of a soil survey by Stiboka, based on 92 boreholes. The deeper soil was investigated by means of three VES, a full coverage by EM-31 measurements, the drilling of 14 cored drillings to a depth of 8 m, in which observation screens were installed, and by a

Fig.6.31. Topographical map of 1850.

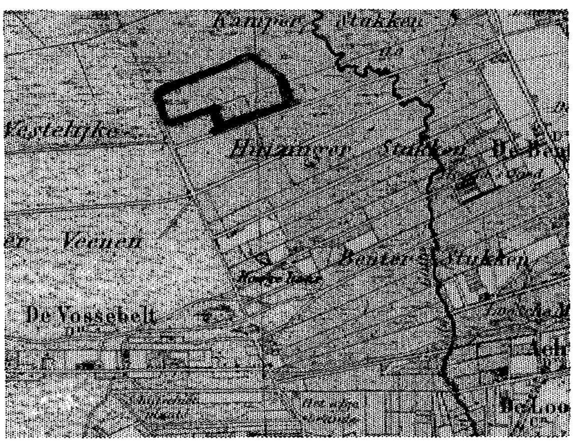


Fig.6.32. The investigations at the farm.

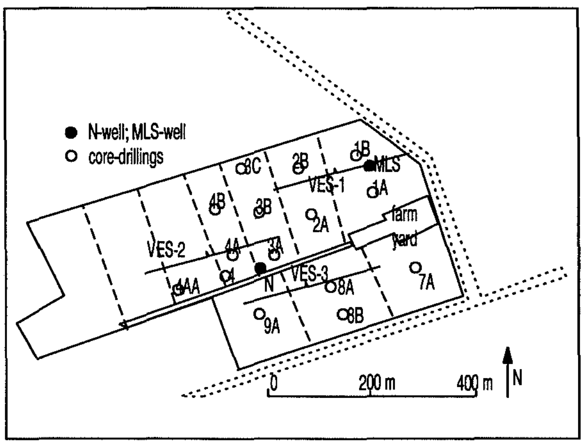


Fig.6.33. The central ditch on the Dalen test farm.

cable-tool drilling (N well). Samples were taken, water levels measured and the wells surveyed. A multi-layer sampler configuration was installed and used.

The landscape at the farm (*Fig.6.33*) bears the marks of the recent reclamation; the land is open with only some tree lanes along roads and canals. The soil is drained by a widely spaced system of broad and deep ditches. In many places a tile drainage has been installed, most probably to dewater the soil above shallow loam layers. The farmland is laid in pasture, except for a few parcels where maize is cultivated.

6.2.5.2. Geohydrological structure

The sedimentological analysis of the cores from the suction drillings was hampered by the fine sandy features of the samples, such that almost no structures became visible after preparation. The layers from 4 to 7 m below surface consisted of uniform fine sand, where eolian deposition has been important. The layers above a depth of 3 m could not be sampled by the cored boreholes. Locally, they contain two superimposed loam layers, the upper one probably being boulder clay and the lower one another type of loam. Above the loam layers, cover sand is present in the topsoil of the test farm, as indicated by the Stiboka survey.

The three VES gave an insight in the structure of the subsurface, the interpretation being shown in *Figs.6.34, 6.35* and *6.36*. The layers to a depth of 1.5 m represent the unsaturated zone consisting of sandy deposits. Below the unsaturated zone, a layer of boulder clay is always present, but only in the case of VES-3 has a second loam layer at a depth of 2 m been interpreted. Further differences result from a loam layer at a depth of 10 m, present in VES-1 and VES-3 and absent in VES-2. Presumably, the observed loam layer forms the basis of a former glacial valley, which has developed in part of the parcel. The valley is interbedded in older fluvio-periglacial deposits, which have their base at a depth of 25 m, where again loam layers are present. The deeper glacial layers are observed below the full parcel. Below these glacial sediments, a sandy subaquifer is present to a depth of 65 m, resting on thick loamy layers, presumably of a Tertiary Age and behaving as the hydraulic base of the aquifer system above it. It may be assumed that the loam layers at a depth of 25 m will exert a limited hydraulic resistance; therefore, the whole system to the depth of 65 m will behave as one single, but locally semi-confined, aquifer. The geohydrological structure of the subsurface has been summarized in *Fig.6.38*.

The structure of the shallow soil also follows from the results of the EM-31 measurements (*Fig.6.37*). The variation in EM-31 values cannot fully be explained by differences in the topsoil, or by the depth of the groundwater table. The Stiboka survey indicated that topsoils and the depth of the shallow groundwater were fairly uniform over the farm parcel. As a consequence, the variation in EM-31 values is largely caused by the presence of the loam layers between a depth of 1 and 3 m below land surface. Most prob-

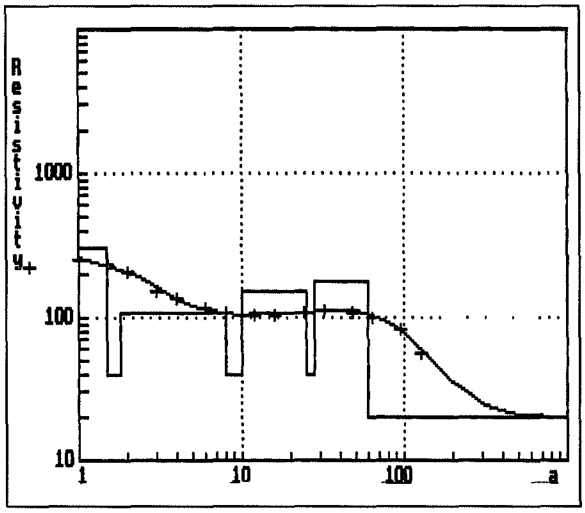


Fig.6.34. VES Dalen-1.

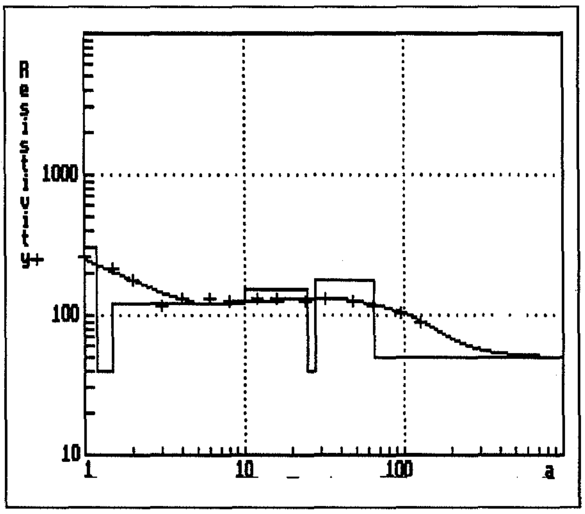


Fig.6.35. VES Dalen-2.

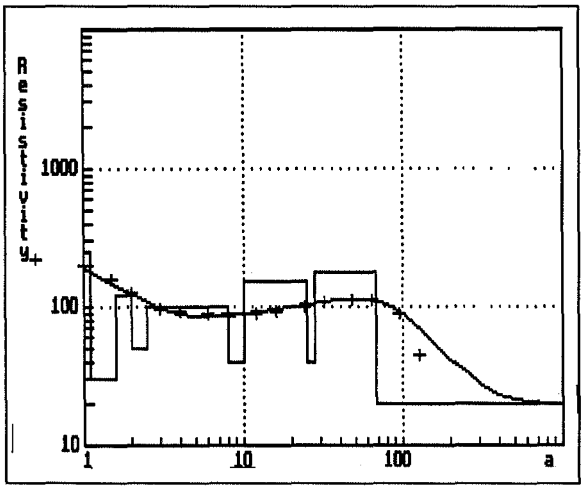


Fig.6.36. VES Dalen-3.

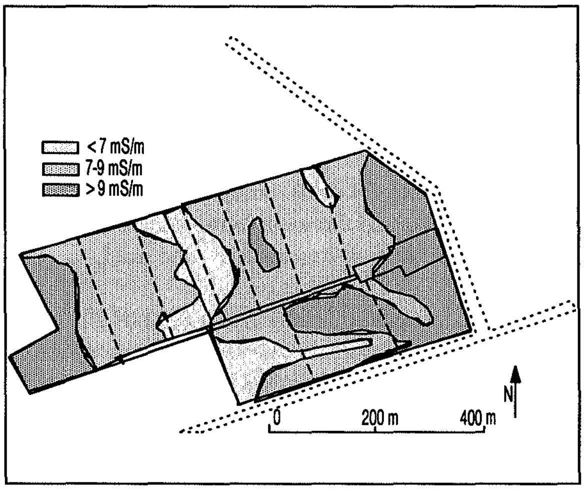
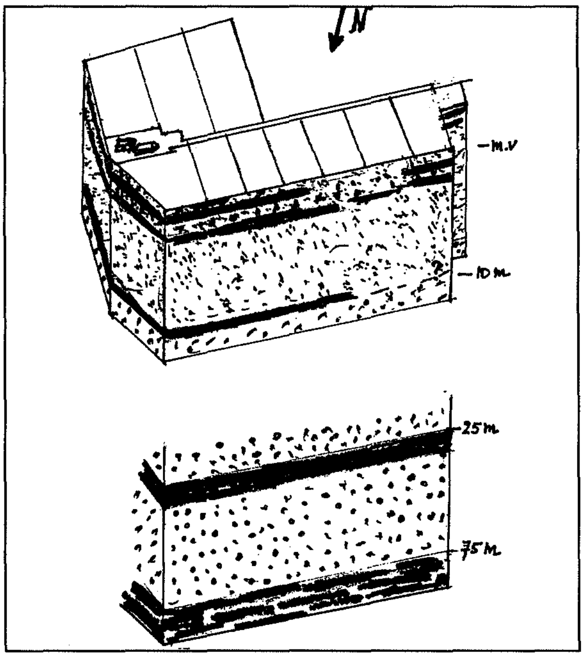


Fig.6.37. EM-31 results (mS·m^{-1}).

Fig.6.38. Soil structure.



ably, the zone with the lowest EM-31 values (less than 7 mS·m^{-1}) represents the area where a boulder clay layer is absent and where the deeper loam layer is only weakly developed. The highest values (more than 9 mS·m^{-1}) probably indicate the areas where both loam layers are present. For intermediate values one of the two loam layers will be absent or poorly developed. At the margins of the parcel relatively high EM-31 values were observed, probably caused by a small depth of the unsaturated zone.

Groundwater isohypses related to a local reference level, based on water levels measured on two different dates in the cored drillings, have been composed. From the isohypses on 19861010 (*Fig.6.39*), gradients in shallow groundwater flow which are small can be derived. A groundwater abstraction at a nearby well field will influence the groundwater flow on the farm. The isohypses observed on 19870511 show a comparable pattern.

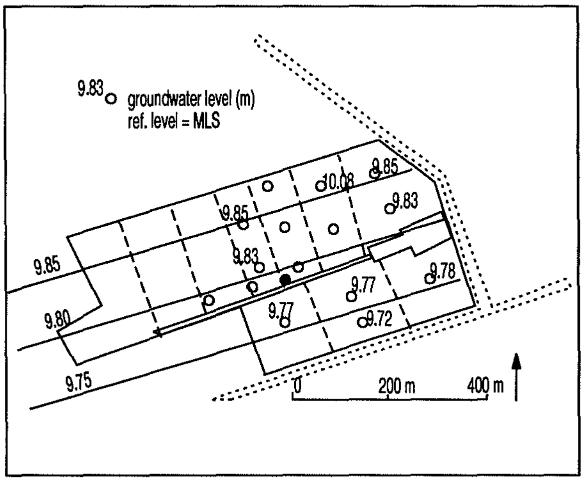


Fig.6.39. Isohypses 861010.

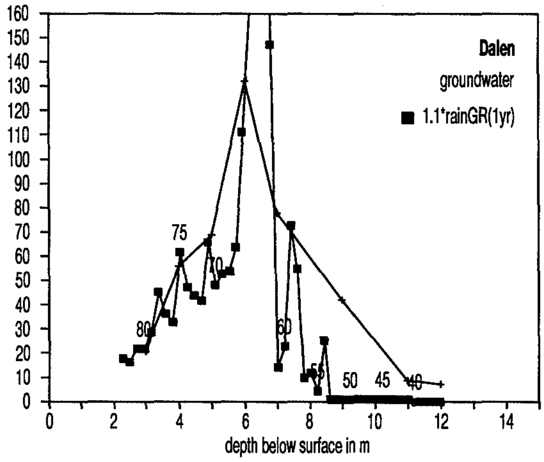


Fig.6.40. ^{3}H content N well.

The interpretation of the measured tritium profile (*Fig.6.40*) in the N well, taking into account that D=65 m, resulted in:

f=1.10 (multiplication factor);

I/p=0.23 $m \cdot a^{-1}$ and I= 78 $mm \cdot a^{-1}$ at p=0.35.

The multiplication factor agrees with the expected value (f=1.08). The downward percolation is much smaller than the average local groundwater recharge. Surficial discharge components, like discharge by tile drainage, will play a role.

6.2.5.3. *Environmental implications*

The nitrate concentrations in the groundwater, taken from the screens of the shallow boreholes, are represented in *Fig.6.41*. The variation largely corresponds to differences in soil types and in groundwater depths at the farm. The average annual application of nitrogen compounds to the farmland of the Dalen test farm in the period before the investigations was in total 635 $kg \cdot ha^{-1}$, divided in 360 $kg \cdot ha^{-1}$ as fertilizer; 150 $kg \cdot ha^{-1}$ as manure slurry and 125 $kg \cdot ha^{-1}$ as field manure. The average concentration of nitrate in the upper groundwater is 44 $mg \cdot l^{-1}$ (as N), representing a total of 87 observations. At a groundwater recharge of 300 $mm \cdot a^{-1}$, estimated from the rainfall excess, it can be calculated that the average annual leaching is 130 $kg \cdot ha^{-1}$, representing 21% of the total dose. The leaching of nitrogen compounds estimated from the NLOAD model constitutes 12% of the total load. The difference between prediction and observations is relatively large, but hard to explain.

The multi-layer sampler observations carried out on the Dalen test farm, represented in *Fig.6.42*, indicate nearly no fluctuations in the concentrations versus depth. The concentrations correspond to values measured in the nearby groundwater. It may be concluded

Fig.6.41. N concentrations in shallow ground water (in $mg \cdot l^{-1}$ as N)

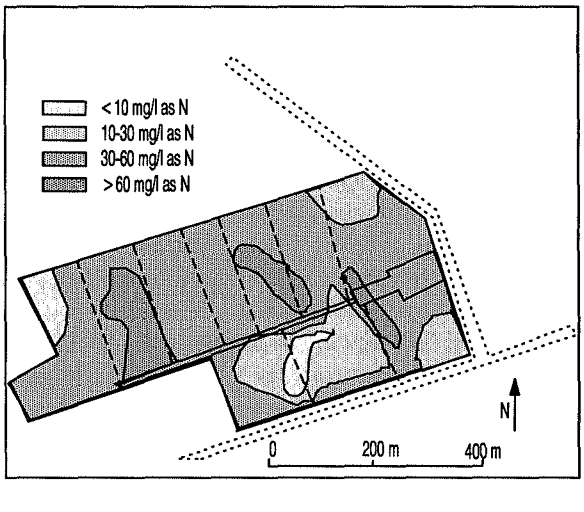
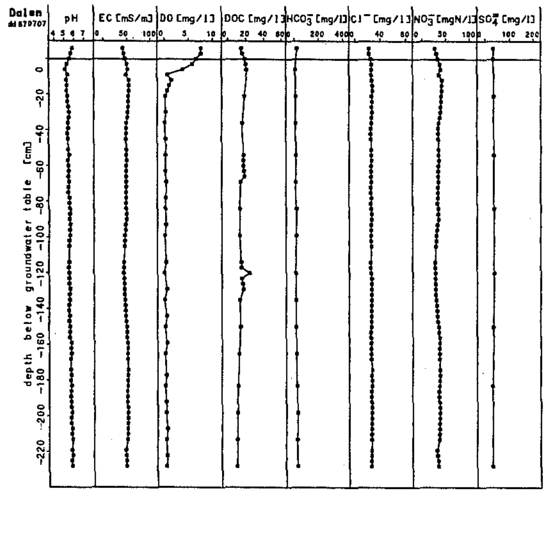


Fig.6.42. Results with multi-layer sampler.



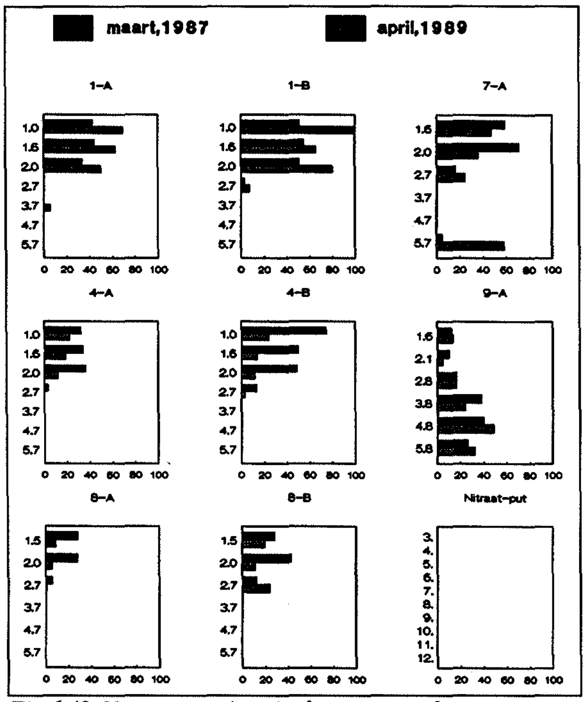


Fig.6.43. N concentrations in deeper groundwater (in mgl^{-1} as N) of the Dalen farm

that a mixing of water with solutes in the unsaturated zone, at least in the form of mixing on a yearly basis, has occurred.

The observed nitrate concentrations in samples from deeper screens are indicated in *Fig.6.43*. The point of recharge and the (large) groundwater travel times may be estimated. In comparing nitrate concentrations in the uppermost saturated zone to the corresponding values in deeper groundwater, the reduction rate may be estimated. It may be concluded that:

30% of the deep observations correspond to shallow values;
20% of the observations indicate a reduction of approximately 50%;
50% of the observations indicate a reduction of more than 80%.

The groundwater concerned is relatively old, probably implying a smaller load of nitrogen compounds at the time of recharge than at present. The reduction rate is roughly 50%.

6.2.6. Tritium data of Groundwater Monitoring Stations

6.2.6.1. East Groningen

The largest part of the sandy area of East Groningen is occupied by the Veenkolonien, a former raised bog, which was fully excavated in the past three centuries. A small zone in the east, Westerwolde, consists of a cover sand area, bounded in the north by ground moraine soils. Before reclamation of the peat bog, the area was almost uninhabitated, except for a few villages in Westerwolde. The reclamation resulted in a regular landscape, where the villages were built in long stretches along the main canals and where the farm parcels had an oblong form. After the introduction of fertilizer before the year 1900, potatoes became the main crop, however, in rotation with other crops. The Westerwolde landscape has conserved some of its ancient forms; villages, farmyards and roads are often surrounded by old tree lanes. Potato cultivation is here too the main type of soil use.

The subsurface is determined by the presence of fluvio-glacial deposits, which, generally, have a low permeability. It is assumed that the base of the upper aquifer is at a depth of 40 m below surface, but where appropriate, another depth is taken. The measured tritium levels in the LMG wells are represented in *Table 6.1*. Average values are:

arable land: n=5; I/p=0.99 $m \cdot a^{-1}$; I=347 $mm \cdot a^{-1}$ (p=0.35);
grassland: n=2; I/p=0.84 $m \cdot a^{-1}$; I=294 $mm \cdot a^{-1}$ (p=0.35);

6.2.6.2. North Drenthe

The northern part of Drenthe is dominated by soils with a boulder clay layer at shallow depth. Within the boulder clay land, broad stream valleys are incised, often in areas where fluvio-periglacial valleys had developed in the Pleistocene Age. Up to 100 years ago, the landscape was dominated by vast heathlands, with some patches of arable land (essen) near the villages. Permanent hay fields were present in part of the stream valleys (madelanden). The heathlands were dry lands in the summer and wet areas in the winter periods. Raised bogs above a peat blanket had developed locally. Most of the land was reclaimed for agriculture in the 1930s, but much forest area is also present. Some of the glacial valleys were filled up with heavy clay ('potclay'), but others with fine sandy sediments. The base of the hydrological system is found at a relatively great depth: 100 m is assumed. The boulder clay is lacking in the stream valleys, but in such cases, it is often replaced by river loams. In many areas, the groundwater recharge is smaller than the rainfall excess, as part of the water is discharged by surficial components. Tritium levels are

Table 6.1. Tritium observations in LMG wells in East Groningen (1-82= upper screen,1982; 3-82=lower screen, 1982)

LMG no.	Location	Land use	1-82 TU	3-82 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
332	ter apel	arable	62	1	0.93	327
333	sellingen	arable	63	1	0.93	327
334	musselk.	arable	58	15	1.15	404
335	stadsk.	arable	31	7	1.19	416
336	omm.wijk	arable	1	1	undet.	undet.
337	o.pekela	arable	88	1	0.65	229
338	veelerv.	arable	30	1	(2.58)	(904)
339	froomb.	arable	36	1	(2.97)	(1040)
341	onnen	grass	60	13	0.96	337
342	groningen	grass	65	1	0.49	170
355	oudezijl	unknown	1	1	undet.	undet.
356	scharmer	arable	56	7	1.08	378

Notes 1. The sampling date may vary from 1982-1984, the indicated date prevails in the area concerned.
2. Undetermined values, values in parentheses and a tritium content of 1 TU often represent cases with upward seepage.

represented in *Table 6.2*, together with an interpretation. With regard to average values, two groups, representing cases with and without a shallow less pervious layer, have been distinguished.

Average results for North Drenthe

arable land	n=1;	$I/p=1.10\ m \cdot a^{-1}$;	$I=385\ mm \cdot a^{-1}$ (p=0.35);
surf. disch. areas:	n=3;	$I/p=0.35\ m \cdot a^{-1}$;	$I=123\ mm \cdot a^{-1}$ (p=0.35);
grass land:	n=2;	$I/p=1.04\ m \cdot a^{-1}$;	$I=364\ mm \cdot a^{-1}$ (p=0.35).

6.2.6.3. South-east Drenthe

The province of Drenthe is characterized by a broad zone of excavated raised bogs at its south-east border. In fact, the digging of peat has continued up to a few years ago in the area south of Emmen, the remaining peat land became a natural reserve. The north-east boundary of the area is a low elevated ridge, the Hondsrug, which also is a water divide, except for the Hunze brook, breaking through it. The rest of the area forms part of the Drenthe boulder clay highland. The

Table 6.2 Tritium observations in LMG wells in North Drenthe (1-84= upper screen,1984; 3-84=lower screen, 1984)

LMG no.	Location	Land use	1-84 TU	3-84 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
21	langelo	arable	51	131	1.10	385
22	schipborg	grass	63	1	0.32	112
25	amen	grass	74	1	0.36	126
26	zeijen	grass	74	1	0.36	126
27	smilde	grass	1	1	undet.	undet.
340	degroeve	grass	25	41	0.94	329
357	depunt	grass	28	39	1.15	406

Notes 1. The sampling date may vary from 1982-1984, the indicated date prevails in the area concerned.
2. Undetermined values and a tritium content of 1 TU often represent cases with upward seepage.

Table 6.3. Tritium observations LMG wells in South-east Drenthe (1-83= upper screen,1983; 3-83=lower screen, 1983).

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
32	schoonloo	forest	97	1	0.32	113
33	exloo	arable	13	1	0.30	107
34	dr.mond	arable	11	6	0.35	121
35	barger	arable	1	1	undet.	undet.
36	nw.amst.	arable	80	1	0.38	134
37	westenes.	grass	1	1	undet.	undet.
38	klijndijk	grass	54	1	0.44	154
39	zweeloo	grass	71	1	0.36	125
40	wijster	grass	1	1	undet.	undet.
45	dalen	grass	34	10	0.46	163
46	zwartem.	forest	1	6	0.88	309
23	gieterv.	grass	1	1	undet.	undet.

Notes 1. The sampling date may vary from 1982-1984, the indicated date prevails in the area concerned.
2. Undetermined values and tritium contents of 1 TU often represent cases with upward seepage.

three different parts of the region also have a different landscape. The central boulder clay district is a half-open land with dispersed villages, still marshy stream valleys and reclaimed heathlands. The Hondsrug has largely been planted with pine forests. The former peat bogs compose a modernly parcelled agricultural area.

In the subsurface of the south-east Drenthe region, a large number of former fluvio-periglacial valleys are present. Furthermore, less pervious layers of a Tertiary Age are at a relatively shallow depth, resulting in aquifers with a low transmissivity. Measured tritium levels are given in *Table 6.3*. Areas with surficial runoff components can be discerned by a groundwater recharge which significantly deviates from the expected range of values:

surf.disch.areas: n=7; I/p=0.37 $m \cdot a^{-1}$; I=130 $mm \cdot a^{-1}$ (p=0.35).

The conclusion is that the downward percolation, in almost the full area, is (much) less than the rainfall excess.

6.2.6.4. South-west Drenthe

South-west Drenthe is the driest part of the province; the soils are sandy and no extensive raised bogs were present. Only in the stream valleys have peaty soils developed. In the South, the Havelter-berg represents a low ice-pushed hill, formed during one of the stages of the Saalian glacial period. A number of traditional villages are dispersed over the area. Like in the rest of the province, farming consisted of the grazing of cattle (sheep) on the heathlands, the manuring of patches of arable land near the villages and the use of stream meadows to produce hay for the winter season.

Boulder clay layers are poorly developed in the shallow soils. Also the glacial valleys are less prominently present than more to the north or to the east. The aquifer system is relatively thick; it reaches a depth of roughly 150 m. Intercalated less pervious clay or loam layers will, generally, not divide the system in fully confined aquifers. Measured tritium levels are given in *Table 6.4*. Average downward percolations are:

grassland: n=5; I/p=0.74 $m \cdot a^{-1}$; I=259 $mm \cdot a^{-1}$ (p=0.35);
forest: n=1; I/p=1.03 $m \cdot a^{-1}$; I=360 $mm \cdot a^{-1}$ (p=0.35);

6.2.6.5 Friese Wouden

The east part of the province of Friesland forms part of the Drenthe boulder clay district and the landscape is also similar. Being at the transition to the marine clay areas, the land is dissected by broad and low valleys, where a peat blanket had developed. The peat was excavated, such that a predominantly sandy soil remained, which has been parcelled in a regular form. The clay and peat cover in the land west of the Friese Wouden is thin. The soil of the Gaasterland area contains the remnants of an end moraine; the soil is sandy and the land is undulating. The Friese Wouden have received their name because in the times before reclamation, the vegetation consisted of a predominantly wet forest. In the east part, many forested areas are still present, but now mostly in the form of a pine forest. More to the west, the land is laid in pasture in order to sustain normal animal hus-

Table 6.4 Tritium observations LMG wells in South-west Drenthe, (1-84= upper screen,1984; 3-84=lower screen, 1984).

LMG no.	Location	Land use	1-84 TU	3-84 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
28	doldersum	forest	42	108	1.03	361
29	veldhuizen	grass	62	27	0.68	240
30	eemster	grass	47	1	(1.82)	(636)
41	hoogeveen	unknown	60	30	0.86	300
42	benderse	grass	60	78	0.74	260
43	weerwille	grass	1	1	undet.	undet.
44	alteveer	grass	44	52	0.79	275
186	darp	grass	33	10	0.74	260

Notes 1. The sampling date may vary from 1982-1984, the indicated date prevails in the area concerned.
2. Undetermined values and tritium contents of 1 TU often represent cases with upward seepage.

bandry. The area considered is larger than the Friese Wouden in a proper sense.

The subsurface consists of thick sandy formations, which constitute a good aquifer, only locally divided in one or more subaquifers, which will never be fully confined. Only at a few places a potclay body has developed, such that the aquifer system is fully confined at the top. The thickness of the aquifer is assumed to be 150 m. The tritium measurements in the LMG wells of the National Groundwater Monitoring system have been represented in *Table 6.5*, together with an interpretation. Average values of groundwater recharge are:

grassland: n=8; $I/p=1.06\ m \cdot a^{-1}$; $I=372\ mm \cdot a^{-1}$ ($p=0.35$);
forest: n=3; $I/p=0.64\ m \cdot a^{-1}$; $I=292\ mm \cdot a^{-1}$ ($p=0.35$);

6.2.7. Summary of results

The interpretation of the available tritium data results in a determination of the downward percolation. The values represent long-term averages and by assuming a value p=0.35, also a long-term averages of the groundwater recharge I can be derived. The groundwater recharge can be compared to the value of precipitation minus the potential evapotranspiration for the various vegetation types, using the following water balance:

$$\mathbf{I=P-E_a-R}$$

with: I= determined downward percolation ($mm \cdot a^{-1}$);
P= long-term average precipitation ($mm \cdot a^{-1}$);
E_a= average actual evapotranspiration ($mm \cdot a^{-1}$);
R= average surficial runoff ($mm \cdot a^{-1}$).

Table 6.5. Tritium observations in LMG wells in East-Friesland, (1-83= upper screen,1983; 3-83=lower screen, 1983).

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
156	murmerw.	grass	1	1	undet.	undet.
157	heerenv.	built-up	41	78	1.11	387
158	bergum	grass	55	53	0.97	339
159	buitenp.	grass	38	1	1.34	468
160	hoogzand	grass	39	1	1.29	453
170	oranjew.	forest	49	22	0.72	251
171	beetst.zw.	forest	76	1	0.56	197
172	bakkeveen	grass	37	64	1.17	409
173	oudehorne	grass	42	1	1.20	422
175	appelscha	forest	27	46	1.22	428
176	oudemird.	grass	33	67	1.02	357
177	spannenb.	grass	51	21	0.83	290
180	nijeholtp.	grass	74	1	0.68	239

Notes 1. The sampling date may vary from 1982-1984; the indicated date prevails in the area concerned.

The water balance can be elaborated in the form:

$$\mathbf{I= P\text{-}E_p\text{-}R+dE}, \text{ or } \mathbf{R\text{-}dE=P\text{-}E_p\text{-}I},$$

with: E_p=potential evapotranspiration for the vegetation concerned;

dE= the sum of the amount of sprinkling water and the reduction in evapotranspiration due to water shortages in the soil in dry periods.

The groundwater recharge I can be determined from the tritium observations and the values of P and E_p can be estimated, implying that the volume of (R-dE) is the only unknown in the equation. Elaboration of the various values determined for (R-dE) yields:

East Groningen:

Veendam test farm; grassland: $P\text{-}E_p\text{-}I= 770\text{-}540\text{-}315=-75$ $mm{\cdot}a^{-1}$;

LMG-wells;arable land: $P\text{-}E_p\text{-}I= 750\text{-}485\text{-}345=-70$ $mm{\cdot}a^{-1}$;

North Drenthe:

Elp test farm; grassland: $P\text{-}E_p\text{-}I= 825\text{-}535\text{-}320=-30$ $mm{\cdot}a^{-1}$;

LMG-wells; grassland: $P\text{-}E_p\text{-}I= 825\text{-}525\text{-}365=-65$ $mm{\cdot}a^{-1}$;

LMG-wells; surface discharge: $P\text{-}E_p\text{-}I= 825\text{-}525\text{-}125=175$ $mm{\cdot}a^{-1}$;

South-east Drenthe:

Dalen test farm; grassland: $P\text{-}E_p\text{-}I= 775\text{-}520\text{-}\ 80=175$ $mm{\cdot}a^{-1}$;

LMG-wells;surface discharge: $P\text{-}E_p\text{-}I= 750\text{-}525\text{-}130=+95$ $mm{\cdot}a^{-1}$;

West Drenthe:

LMG-wells; grassland: $P\text{-}E_p\text{-}I= 840\text{-}535\text{-}260=+45$ $mm{\cdot}a^{-1}$;

LMG-wells; pine forest: $P\text{-}E_p\text{-}I= 840\text{-}640\text{-}360=-160$ $mm{\cdot}a^{-1}$;

Friese Wouden:

LMG-wells; grassland: $P\text{-}E_p\text{-}I= 840\text{-}540\text{-}370=-70$ $mm{\cdot}a^{-1}$;

LMG-wells; pine forest: $P\text{-}E_p\text{-}I= 845\text{-}600\text{-}295=+50$ $mm{\cdot}a^{-1}$;

The value of (R-dE) is, in many cases, negative. It may be assumed that the surface runoff (R) can be neglected for most of the cases considered, implying that often the sum of a reduction in evapotranspiration and the applied amount of sprinkling water is in the order of 70 $mm{\cdot}a^{-1}$. The calculated values for the groundwater recharge, based on the tritium levels, correspond to values which were estimated from regional water balances. Furthermore, it may be concluded that in areas where a surficial discharge is expected, the groundwater recharge is roughly GR=100 $mm{\cdot}a^{-1}$. A first estimate of the rainfall excess being I=300 $mm{\cdot}a^{-1}$, it may be assumed that the average amount of surficial discharge is in the order of magnitude of SR=200 $mm{\cdot}a^{-1}$. A further discussion of the results, in combination with results for the other districts, follows in the concluding chapter.

6.3. The eastern sand district

6.3.1. Geography and landscape

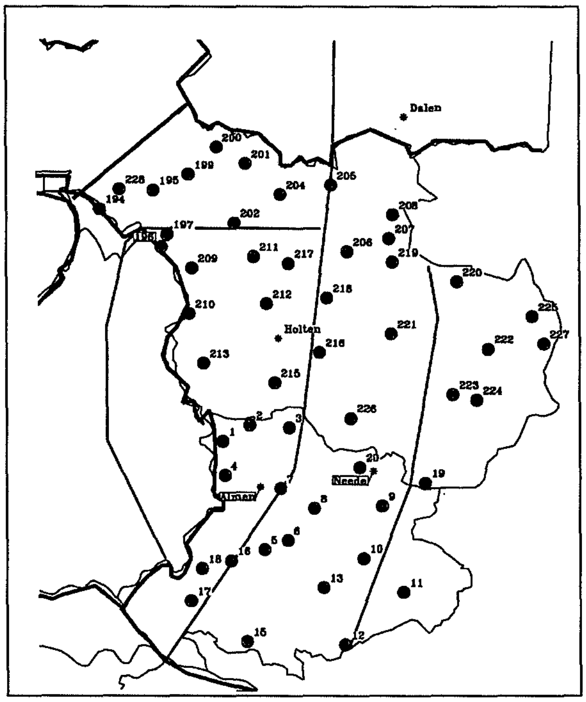
The eastern sand district (*Fig.6.44*) covers the eastern parts of the provinces of Gelderland and Overijssel, where the soil is predominantly sandy. Subregions are North Overijssel (Vechtstreek), Salland, Central Overijssel, Twente and Achterhoek.

1. North Overijssel (Vechtstreek)
   The northern part of Overijssel consists of the broad valley of the River Vecht, which overlies a buried glacial valley. The land is flat and open; large parts were covered with a thin peat cover, which now has disappeared. At some places near the river, inland river dunes have developed, with an accompanying dune soil. In other areas, raised bogs, which were later exploited for peat excavation, had developed.
2. Salland
   The valley of the River IJssel is also situated on top of a buried glacial basin, bordered in the west by the Veluwe hills and in the east by the hills of the Overijsselse Heuvelrug. The broad and deep basin has been filled in with relatively coarse Rhine sediments. The Salland region occupies the east bank of the IJssel valley. The land has a sandy soil and is relatively well drained by a large number of local streams. Along the IJssel, a slightly elevated zone with river clay soils adjoins the river.
3. Central Overijssel
   East of the Overijsselse Heuvelrug, a stream, Regge, runs to the north in a relatively broad valley and ultimately discharges into the Vecht. The eastern boundary is the relatively elevated land of Twente. Because of the incoming water flows and the low elevation, peat layers developed in many spots, which were even commercially exploited in the northern part, at Vriezenveen. Villages were built on the somewhat more elevated fringes of the valley, on the Overijsselse Heuvelrug and in Twente.
4. Twente
   The East-Netherlands Plateau of Tertiary layers and even older consolidated rocks comes close to surface in the Twente area. In many places, the shallow soil consists of thick clay layers, no aquifer system being present. However, the area is dissected by buried glacial valleys, which were often filled in with sandy deposits, forming isolated aquifers. At other places, the Tertiary sediments were deformed into push ridges, with a nearly impervious soil. The hydrological situation is complicated. Important industrial centres and settlements have arisen in the last 150 years.
5. Achterhoek
   The eastern part of the Achterhoek also belongs to the East-Netherlands Plateau. The area more to the west consists of a sandy fluvial plain with a permeable subsurface and drained by a regular pattern of local streams. The region is characterized by varying elements, like fluvial plains, old river courses, peaty swamps and sandy push ridges. Formerly, a large area of wasteland was present, but the main type of land use nowadays is permanent pasture. Intensive animal husbandry has strongly developed in recent years.

6.3.1. Hydrogeological situation

The sandy subsurface of the eastern sand district was mainly deposited by the River Rhine during the Pleistocene age, but parts of the subsurface were reworked by glacial phenomena. Younger sediments have filled in a large glacial valley (*Fig.6.45*), where the present course of the River IJssel runs. In the middle of the district, a ridge of low hills originated when the subsurface was pushed by Pleistocene glaciers. The East-Netherlands Plateau is an elevated terrace of a geologically old age, parts of it have also been pushed by the ice. With regard to the hydrogeological situation, the area can be divided in two different zones. In the east, Tertiary clay layers ap-

Fig.6.44. LMG wells and the location of the test farms in the eastern sand district.



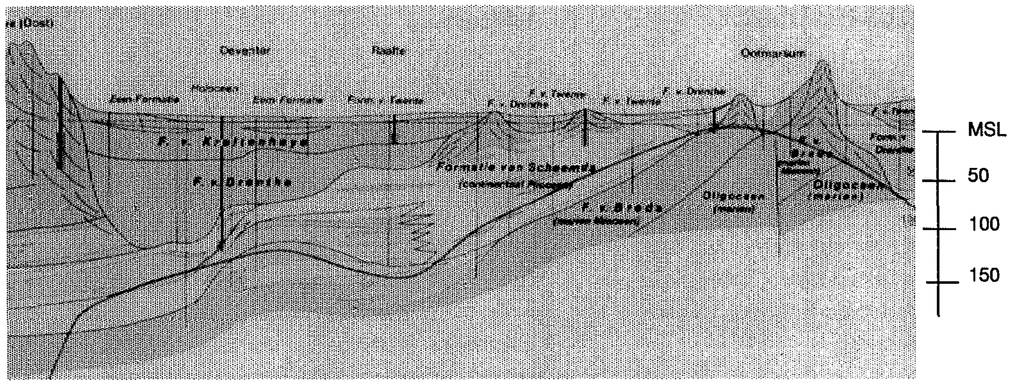


Fig.6.45. Hydrogeological cross-section of the eastern sand district according to Jelgersma (1977)

proach land surface, no exploitable aquifer system being present, except in some places where glacial valleys have been filled in with sandy sediments. In the west, the surbsurface contains older and younger Pleistocene sandy sediments, locally separated by thin Eemian loam layers. Over large parts of the district, the Pleistocene and Upper Tertiary sediments constitute one single and unconfined aquifer. In the west, the clay filling of the former glacial valley may confine the sand layers underneath, thus creating two separate aquifers.

The hydrology of large regions in the eastern sand district was intensively studied by various institutes, co-ordinated by the provincial administrations. In the province of Overijssel, the 'Werkgroep Hydrologisch Onderzoek Overijssel' (Working Group on Regional hydrological investigations) was active during the years 1969-1974. In Gelderland, de 'Commissie Bestudering Waterhuishouding Gelderland' (CWG; Committee on Water Management Studies) and its predecessors were active for a large number of years before 1975. On the basis of discharge measurements, RID (1978) composed long-term water balances for different parts of Overijssel, resulting in:

Salland: P=770 mm·a^{-1}; E_a=430 mm·a^{-1}; I=340 mm·a^{-1};
Regge basin: I=320 mm·a^{-1} (average stream discharge 24 years);
Vecht basin: I=336 mm·a^{-1} (average river discharge 20 years);

Colenbrander (1970) summarized the CWG investigations in the Leerinkbeek area. He arrived at the following water balance for the Leerinkbeek area in the north-east part of the Achterhoek on the basis of stream discharges for the period 1952-1966:

Leerinkbeek basin: P=810 mm·a^{-1}; E_a=440 mm·a^{-1}; I=370 mm·a^{-1};

Ernst et al. (1970) composed a water balance for another subregion in the Achterhoek. They arrived at the conclusion that the regional groundwater flow only transported a relatively small part of the excess water. Stricker (1981) compared the various methods to estimate the actual evapotranspiration with the values computed from water balances for the "Hupselse beek" watershed in the period 1976-1978. He remarked that the approximation E_a=0.7*E_0(Penman) corresponded better to the values for E_a, derived from stream discharges, than E_a=0.8*E_0.

6.3.3. The Holten test farm

6.3.3.1. Situation and investigations

The Holten test farm (*Fig.6.46*) is situated in an area called Holter-broek, forming part of a zone of 'broek' areas. These run parallel to a row of hills and constitute the Overijsselse Heuvelrug. The name 'broek' indicates a marshy area, often with a willow and alder vegetation. From east to west, characteristic names are given to the successive areas:

- Holter-berg, an ice-pushed ridge, planted with pine trees;
- Holter Enk, arable land on the hill flank, in former times fertilized with the dung of cattle grazing in the wastelands;
- Vletgaars-maten, a low-lying area with pastures;
- Holter-broek, originally a marshy area.

The broek zone is a seepage area captating the groundwater which was and is recharged at the Holterberg, a sandy hill, formerly with a heather vegetation. In 1850 (*Fig.6.47*), the Holterbroek had already been reclaimed. The land was drained by a dense network of ditches.

The topsoil of the test farm still bears the marks of the former broek situation. According to the Stiboka (1988) soil survey, the soil contains peaty components and has shallow groundwater tables in many places. But there is also a zone with sandy soils, hav-

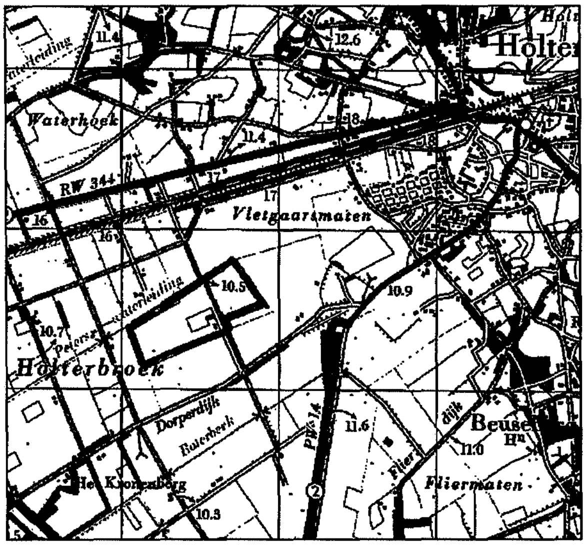


Fig.6.46. Situation of the Holten test farm.

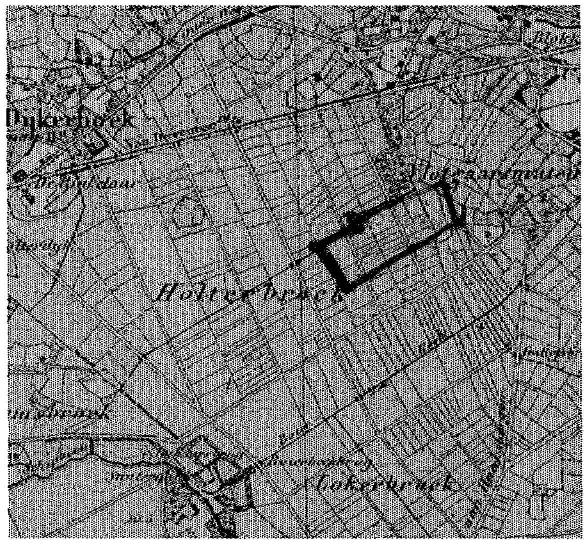


Fig.6.47. Topographical map of 1850.

ing relatively deep groundwater levels. In a land improvement project, the soil features were changed by reworking the peaty components. In the farm parcel, the base of a former glacial valley is presumably situated at a depth of 25 m. Between that depth and a depth of 100 m, Pleistocene sediments, belonging to the Formations of Tegelen and Maassluis are present (RGD,1975). These sandy layers rest upon a base layer of loamy and clayey sediments, probably of a Tertiary age. The filling in of the valley was finished by the deposition of recent river sediments and, at the top, by layers of cover sand.

The investigations on the farm (*Fig.6.48*) consisted of a soil survey by Stiboka, based on 91 boreholes. The deeper soil was investigated by means of four VES at the farm, a full coverage by EM-31 data, the execution of 10 cored suction drillings to a depth of 8 m, in which observation screens were installed, and the installation of a cable-tool drilling (the N well). Samples were taken, water levels measured and the wells surveyed. A multi-layer sampler was installed and used.

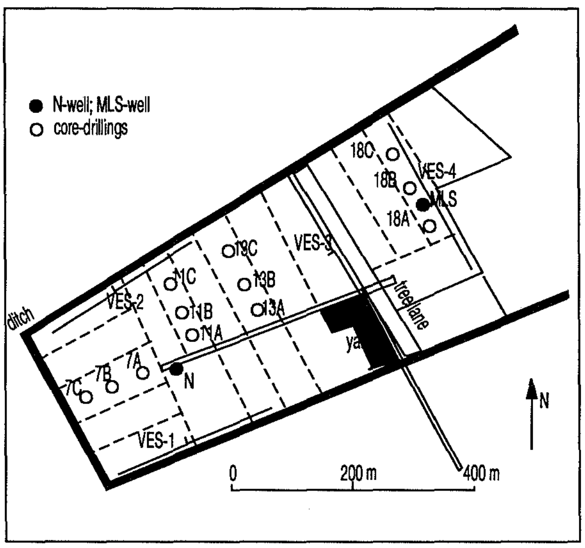
In a recent project of land improvement, the parcels were enlargened; the drainage of seepage water and rainfall excess is realized by a system of tile drainage. The land is open and dominated by the low hills in the east (*Fig.6.49*). The area is used for permanent pasture with a few maize parcels for animal fodder. West of the Holterbroek, the Salland region comprises a sandy area, dewatered by a system of streams.

6.3.3.2. *Geohydrological structure*

The cores from the suction drillings indicated that the shallow subsurface, down to a depth of 5 m, consists predominantly of fine sandy sediments of the Twente Formation, alternating with coarser sediments of a fluviatile origin belonging to the Kreftenheye Formation . The thickn ess of the layers with coarse components is larger in the north-west part of the farm parcel, but they are not fully absent in the other drillings. The coarse sediments were probably deposited by a rather large river course. The shallow soil might represent an abandoned river bed, with course sediments in the centre and finer deposits in the adjoining basins.

The subsurface was investigated by means of the four VES, which showed large differences. The interpretation of VES-2 and VES-4 are depicted in *Figs.6.50* and 6.51 and all results are summarized in *Table 6.7.* Layer 1 represents the unsaturated zone which consists of sandy layers of a variable texture, locally

Fig.6.48. The investigations on the farm.



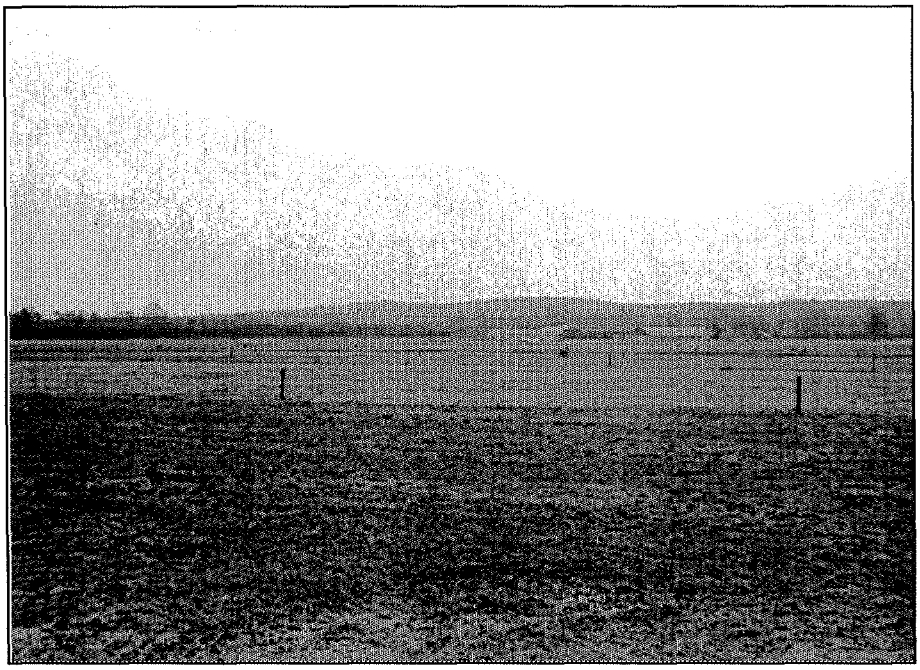


Fig.6.49. The Holterberg seen from the farm.

containing peaty components. The layers 2a and 2c represent fine sandy layers; VES-2 is the only case were a layer 2b, containing coarse sand, maybe with less polluted seepage water, was interpreted. Further differences result from the presence of a loamy layer at a depth of approximately 10 m, absent in the western VES and present in the eastern part of the parcel.

The structure of the shallow subsurface can also be derived from the results of the EM-31 survey (*Fig.6.52*). A meander of relatively low values starts in the north-west corner of the parcel and continues to the east. As well, areas are present with values larger than 10 mS·m^{-1}, maybe representing former river basins where finer sediments were deposited.

Presumably, the loam layers observed at a depth of 10 m were deposited in a former glacial valley. The valley was filled in with fluvio-periglacial deposits, with their base at a depth of 25 m, where again loam layers are present. Below the glacial sediments, a deeper sandy subaquifer reaches to a depth of roughly 100 m, where it rests on thick loamy layers, presumably of a Tertiary age and behaving as the hydraulic base of the aquifer system above it. A remarkable feature is that in VES-2, the base is interpreted at a depth of only 80 m, leading to the interpretation that a strong upward seepage exists, attracting brackish groundwater from below. As it may be assumed that the loam layers at a depth of 25 m will exert a limited hydraulic resistance, the whole system

Fig.6.50.VES Holten-2.

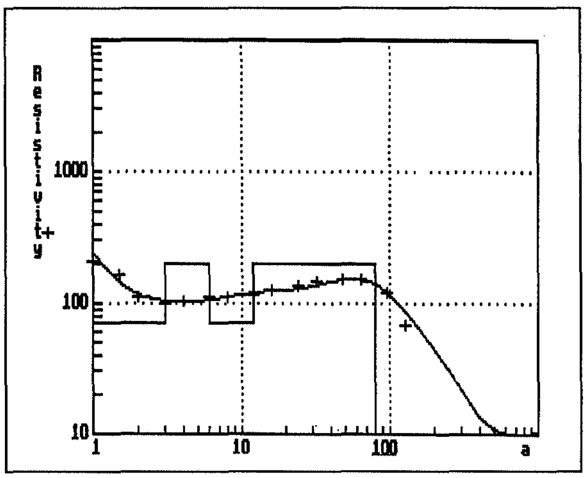


Fig.6.51. VES Holten-4.

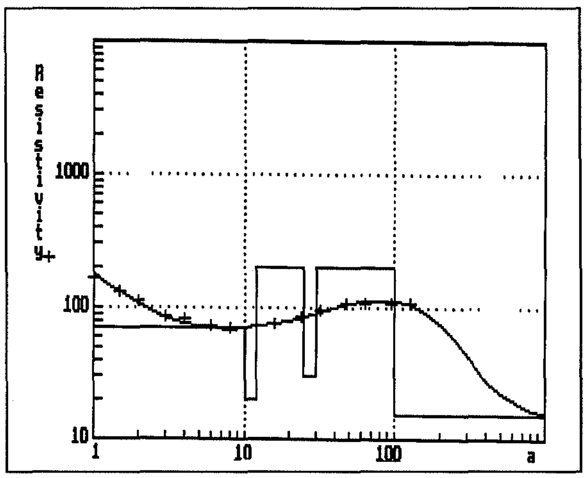


Table 6.7. Summary of the VES interpretations at Holten

	Holten-1		Holten-2		Holten-3		Holten-4	
Layer	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm
1	0.6	350	0.7	400	1.0	150	0.8	250
2a	-	-	3.0	70		-	-	.
2b		-	6.0	200	-	-	-	-
2c	11	70	11	70	10	70	10	70
3	-	-	-	-	12	15	12	20
4	25	200	25	200	28	200	25	200
5	35	30	-	-	39	30	30	30
6	100	200	80	200	110	200	100	200
7		20		10		25		15

to the depth of 100 m will behave as one single aquifer. The geohydrological structure of the subsurface has been summarized in *Fig.6.53*.

Because of the sandy subsurface, it may be expected that the rainfall excess will recharge most of the shallow groundwater, which will transport it to the nearby drainage facilities. In the former situation, the area was drained by many small ditches, which were replaced by a system of tile drainage, discharging into only a few broad and deep ditches.

The groundwater contours in *Fig.6.54*, indicating a flow dominated by local conditions, could only be based on a limited number of observations. The tritium profile, measured in the N well is noteworthy. The upper screens, down to a depth of roughly 5 m, show tritium levels which can be interpreted in the sense of a downward groundwater flow, but the values from deeper screens are lower than expected. The reason probably is that in the deeper layers, upward vertical flow components, bringing in seepage water from the hills, will prevail. The interpretation of the upper tritium profile (*Fig.6.55*) leads to:

f=1.07 (regional factor);
I/p=0.93 $m{\cdot}a^{-1}$ and I= 325 $mm{\cdot}a^{-1}$ at p=0.35.

The regional factor corresponds to the expected value (f=1.10). The downward percolation is in agreement with the expected rainfall excess. The decrease in tritium level at a greater depth is probably related to a part of seepage water increasing with depth. A transition between locally recharged, downward penetrating groundwater and the upward flow of regional seepage water, is found at a depth of 9 m at the location of the N well. But already at a depth of 5 m, an upward seepage may occur. The transition will have a variable depth over the farm parcel, because it may be expected that the seepage conditions will vary.

Fig.6.52. EM-31 values ($mS{\cdot}m^{-1}$).

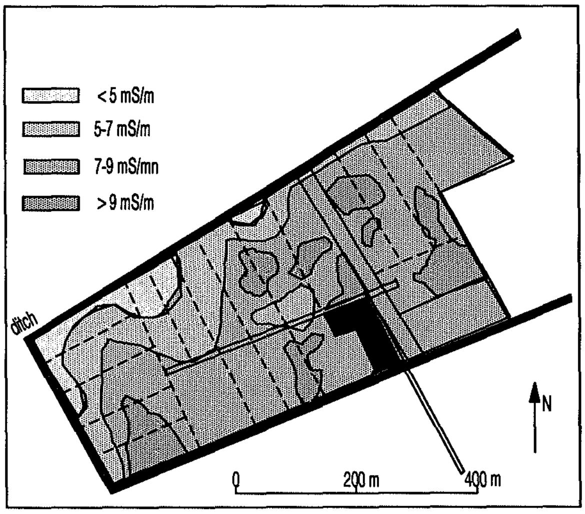
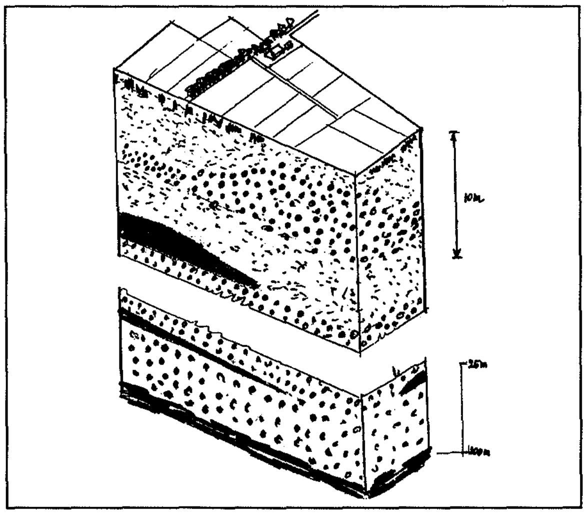


Fig.6.53. Soil structure of the Holten farm.



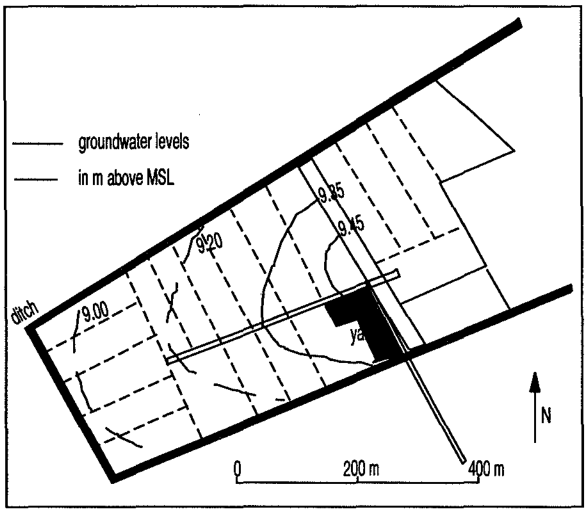


Fig.6.54. Isohypses 870401.

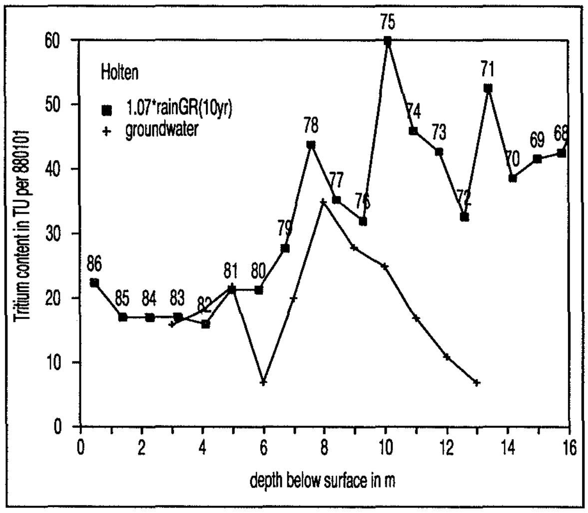


Fig. 6.55. ^3H content N-well

6.3.3.3. Environmental implications

The nitrate concentrations on top of the saturated groundwater, taken from the screens of the shallow boreholes and represented in *Fig.6.56*, show a variation from 0 to more than 100 mg·l^{-1} as N. The variation partly corresponds to the differences in soil types and in groundwater depths on the farm. However, also seepage water, bringing in water with low nitrate concentrations, plays a role. The average annual application of nitrogen compounds to the farmland of the Holten test farm in the years before the investigations totalled 567 kg·ha^{-1}, divided in 327 kg·ha^{-1} as fertilizer; 159 kg·ha^{-1} as manure slurry and 82 kg·ha^{-1} as field manure. The average concentration of nitrate in the upper groundwater is 18 mg·l^{-1} (as N), representing a total of 84 observations. At a groundwater recharge of 325 mm·a^{-1}, estimated from the tritium data, it can be computed that the average annual leaching is 58 kg·ha^{-1}, representing 10% of the total dose at land surface. The leaching of nitrogen compounds estimated from the NLOAD model constitutes 9% of the dose at land surface.

The multi-layer sampler observations executed at the Holten test farm, represented in *Fig.6.57*, indicate nearly no fluctuations in the measured concentrations versus depth. The nitrate concentrations are lower than the values measured in the nearby saturated groundwater, probably indicating the effect of an upward seepage of less polluted water.

The observed nitrate concentrations in samples from deeper screens have been indicated in *Fig.6.58*. No

Fig.6.56. N concentrations of shallow groundwater (in mg·l^{-1} as N).

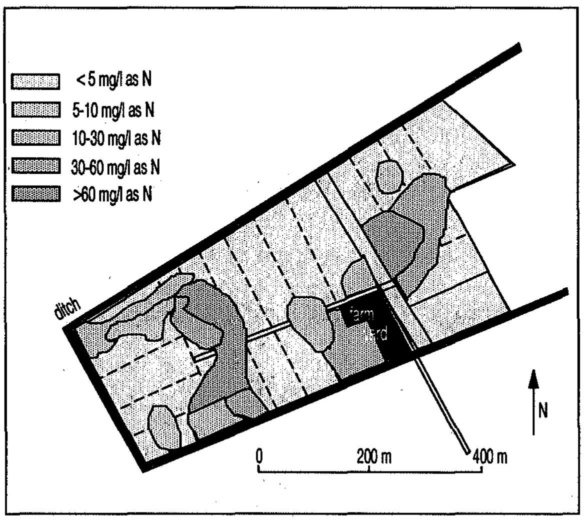
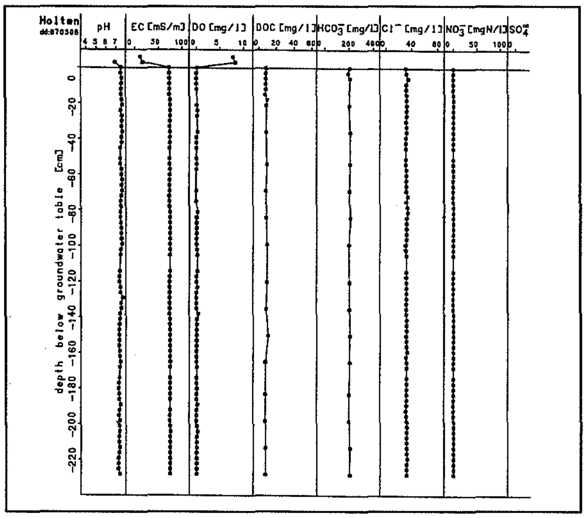


Fig.6.57. Results of the multi-layer sampler.



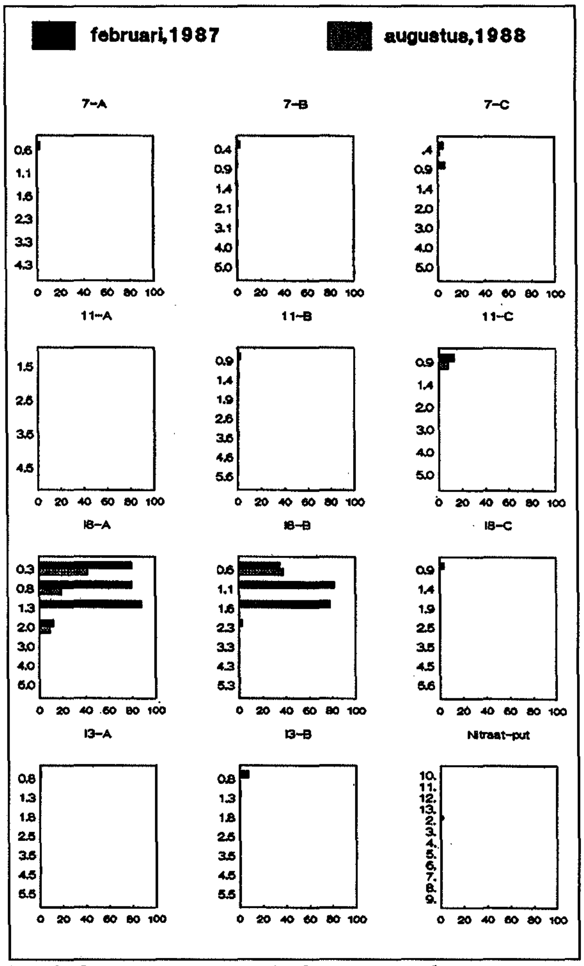


Fig.6.58. N concentrations in deeper groundwater (in mg·l^{-1} as N) of the Holten farm.

conclusions can be drawn because an upward seepage will determine the nitrate concentrations.

6.3.4. The Almen test farm

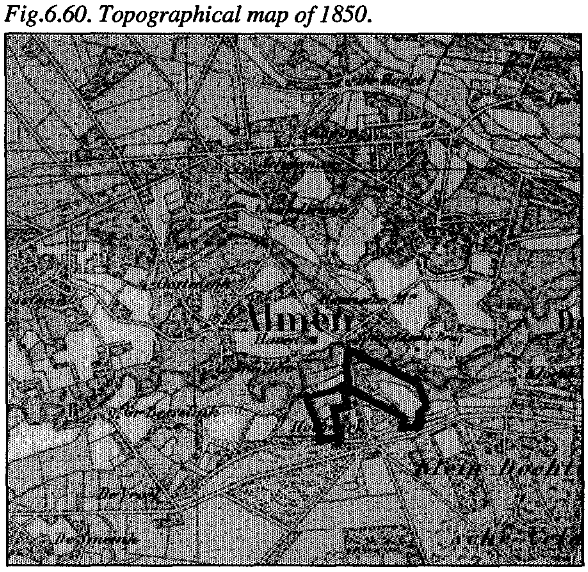
6.3.4.1. Situation and investigations

The Almen farm (*Fig.6.59*) occupies a low hill on the south side of the Berkel stream. The elevation is the northermost part of a system of inland dunes, formed by windblown cover sands. The main body of the cover sand ridges was planted with pine trees. But the isolated elevation at the farm has already for centuries been in use as agricultural land. The low hill has been artificially elevated by the deposition of manure in order to fertilize the land. This practice has elevated the hill roughly one metre and has covered it with a black soil. The 1850 topographical map (*Fig.6.60*) already indicated the same features as are present now; only the course of the stream was canalized and the land of the "enk" has turned into permanent pasture.

According to the Stiboka (1988) survey, the shallow soil consists of humus 'enk-eerd' soils on the elevated ridge, and of sandy soils and river loams in the stream forelands. Locally, even peat layers were formed. The deeper subsurface is part of the large glacial valley underneath the IJssel lowland to a depth of 70 to 80 m. The deeper parts of the valley have been filled in with fluvio-periglacial sediments of the Drenthe Formation. The more shallow deposits belong to the Kreftenheye Formation, which contains mostly coarse sandy sediments from the River Rhine. The uppermost layers of the farm soil were deposited during the last stage of the Pleistocene age and form part of the Twente Formation, predominantly consisting of fine sandy sediments. The base of the former glacial valley will

Fig.6.59. Situation of the Almen test farm.

Fig.6.60. Topographical map of 1850.



probably consist of clay and loam layers, resting on sandy and loamy sediments of a Lower Pleistocene and even Tertiary age. Most probably these earlier and deeper sediments will contain brackish groundwater (DGV-TNO, Groundwater Map).

The investigations on the farm (*Fig.6.61*) consisted of a soil survey by Stiboka, based on 79 boreholes. The deeper soil was investigated by means of four VES, a full coverage by EM-31 data, carrying out 9 cored drillings to a depth of 8 m, in which observation screens were installed, and the installation of a cable-tool drilling (N well). Samples were taken, water levels measured and wells surveyed. Also, on the Almen farm, a multi-layer sampler was installed in the soil and used for sampling.

The elevated land, which locally is called an 'enk', completely belongs to the test farm. The Berkel attacked the east flank of the elevation, such that a steep slope and narrow foreland, covered by a clayey soil originated (*Fig.6.62*). A few hundreds of metres more to the north, the stream reassumes a westerly course and the valley becomes broader again. The west part of the farm parcel is situated in that valley.

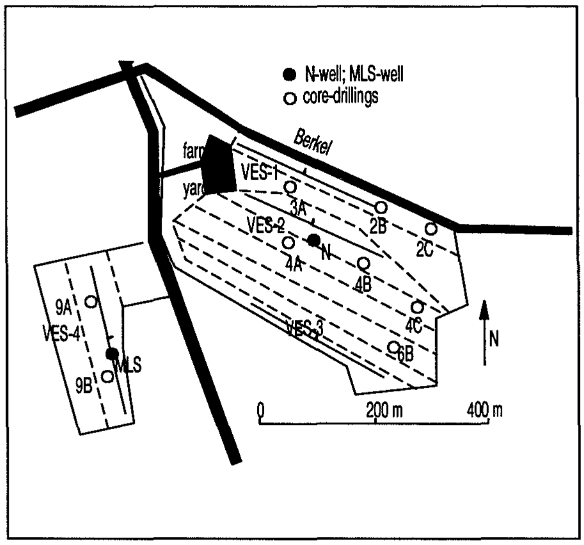


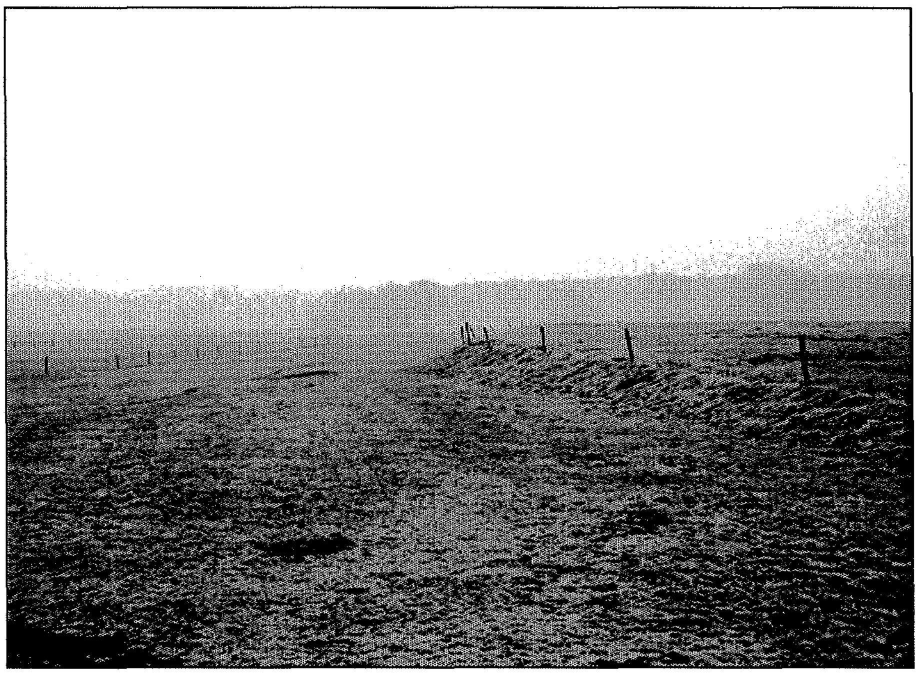
Fig.6.61. The investigations on the farm.

6.3.4.2. Geohydrological structure

The suction drillings indicated that the shallow layers, down to a depth of roughly 6 m, consist of an intercalation of aquatic and eolian sediments. Apparently, the water flow in predecessors of the present stream was intermittently blocked by an influx of windborne cover sands during the Weichselian cold period in the Late-Pleistocene age. Both types of sediments show different structures, but they mostly consist of relatively coarse sand. The deeper sand layers, at a depth of 8 m and probably belonging to the Kreftenheye Formation, have a finer texture, maybe due to their situation on top of the formation.

The subsurface was investigated by means of four VES, which also indicated the difference between enk and lowlands. The interpretation of VES-1 and VES-4 is shown in *Fig.6.63* and *6.64* and all results

Fig.6.62. Brook and enk on the east side of the parcel.



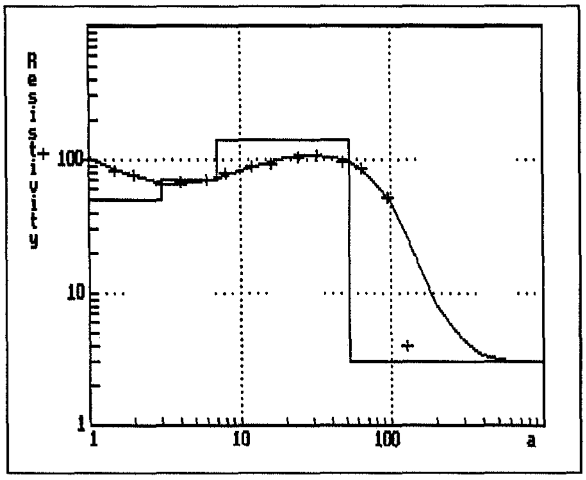


Fig.6.63. VES Almen-1.

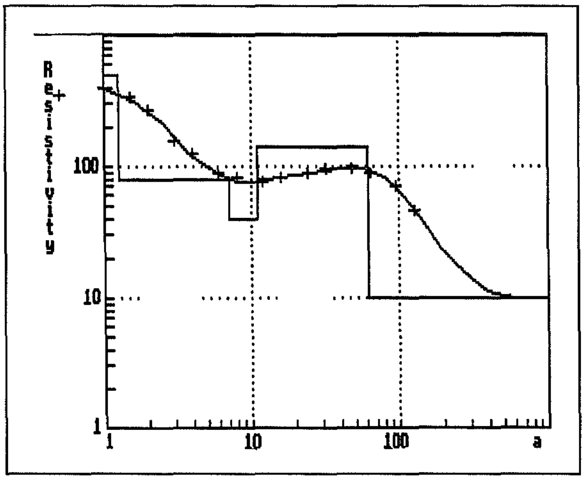


Fig.6.64. VES Almen-4.

are summarized in *Table 6.8.* Layers 1a and 1b represent the unsaturated zone, which consists of sandy layers at the enk but contains loamy and peaty components at VES-1. Also layer 2a is only present in VES-1, where it indicates the presence of a shallow loam layer. Layer 2b represents the sandy layers investigated by the cored samples. Furthermore, a loamy layer is present at a depth of approximately 10 m, which is not observed in VES-1.

The general features of the shallow subsurface follow from the results of the EM-31 survey (*Fig.6.65*). The difference in the high 'enk' soils and the valley soils results in EM-31 values lower than 5 $mS \cdot m^{-1}$ at the enk; local variations will express the differences in the depth of the groundwater table. Values between 6 and 8 $mS \cdot m^{-1}$ were determined in the western parcel. Still higher values were observed in the narrow stream foreland near the farm, which are caused by the presence of loam and peat layers in the shallow soil. Apparently, the boundary between enk and foreland had a slightly more irregular form than the present parcel boundary.

The loam layer at a depth of 10 m is perhaps the top of the Kreftenheye Formation, developed as fine sediments. The valley is further filled in with fluvio-periglacial deposits, which have their base at a depth of roughly 70 m. Here, loamy layers are present, probably constituting the hydraulic base of the aquifer system above it. A remarkable feature is that the base is interpreted at a variable depth, leading to the interpretation that, locally, an upward seepage exists, attracting brackish groundwater from below. This implies a variable top of the base layer of a relatively low resistivity. As it may be assumed that the loam layers at a depth of 10 m will exert a limited hydraulic resistance, the whole system, to the depth of minimally 60 m, will behave as one single aquifer. The geohydrological structure of the subsurface has been summarized in *Fig.6.66.*

The groundwater isohypses, observed in the spring of 1987, are represented in *Fig.6.67*, showing the groundwater drainage by the Berkel. Further landinward the pattern becomes more regular, corresponding to the regional pattern.

Table 6.8.. Summary of the VES interpretations at Almen

	Almen-1		Almen-2		Almen-3		Almen-4	
Layer	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm	depth m	res. Ωm
1a	-	-	0.3	550	0.3	400	0.3	350
1b	1.0	120	3.0	1000	2.0	550	1.4	500
2a	3.0	50	-	-	-	-	-	-
2b	7	70	7	80	7	60	7	80
3a	-	-	9	20	10	40	11	40
3b	53	140	65	150	70	140	65	140
4		3		3		10		10

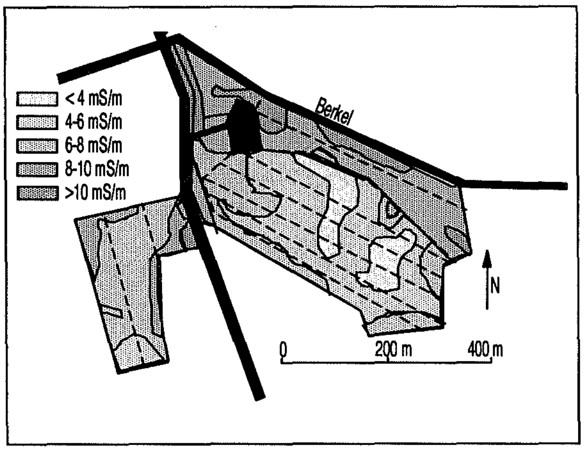


Fig.6.65. EM-31 values (mS·m⁻¹).

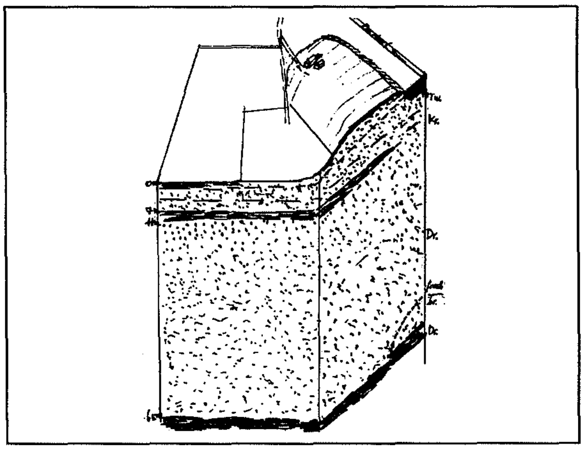


Fig.6.66. Soil structure of the Almen farm.

The tritium profile measured in the N well is given in *Fig.6.68.* The interpretation, based on D=70 m, results in:

f=1.15 (regional factor);

I/p=0.80 m·a^{-1} and I= 280 mm·a^{-1} at p=0.35.

The regional factor is in agreement with the expected value (f=1.12). The 'enkeerd' soil features, implying a considerable moisture-retaining capacity, restrain a possible reduction of the potential evapotranspiration. The groundwater recharge is relatively small.

6.3.4.3. Environmental implications

Nitrate concentrations in the uppermost saturated groundwater, taken from the shallow boreholes and represented in *Fig.6.69*, show a large variation corresponding to the differences in soil types and in groundwater depths on the farm. The average annual dose of nitrogen compounds to the farmland of the Almen test farm in the period before the investigations totalled 805 kg·ha^{-1}, divided in 415 kg·ha^{-1} as fertilizer; 285 kg·ha^{-1} as manure slurry and 105 kg·ha^{-1} as field manure. The average concentration of nitrate in the upper groundwater is 54 mg·l^{-1} (as N), representing a total of 59 observations. At an estimated groundwater recharge of 280 mm·a^{-1}, it can be computed that the average annual leaching is 150 kg·ha^{-1}, representing 19% of the total dose. The leaching of nitrogen compounds, estimated from the NLOAD model constitutes 14% of the gift. The observed leaching of nitrogen roughly agrees with the predictions.

The multi-layer sampler observations executed at the Almen test farm, represented in *Fig.6.70*, indicate nearly no fluctuations in the measured values versus depth. The concentrations correspond to the values measured in the nearby saturated groundwater, indicating the effect of mixing on a yearly basis in the unsaturated groundwater.

The observed nitrate concentrations in samples from

Fig.6.67. Isohypses 870407.

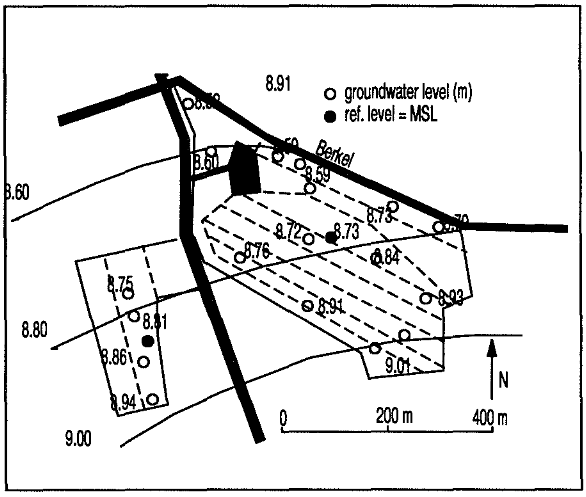
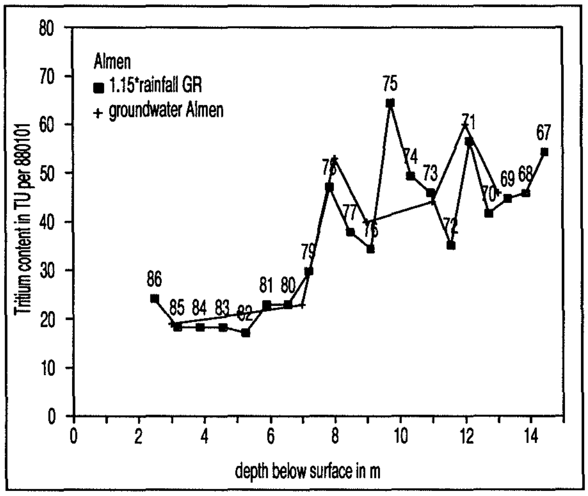


Fig. 6.68. ³H content N-well



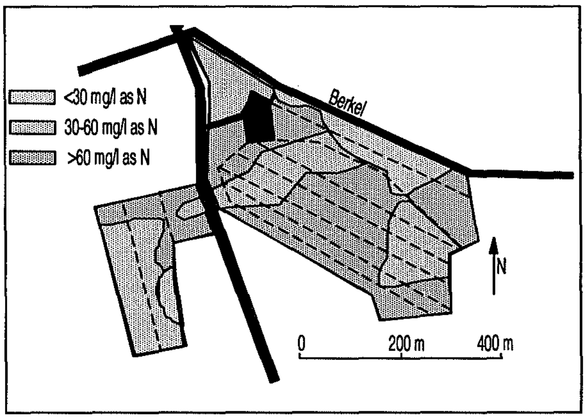
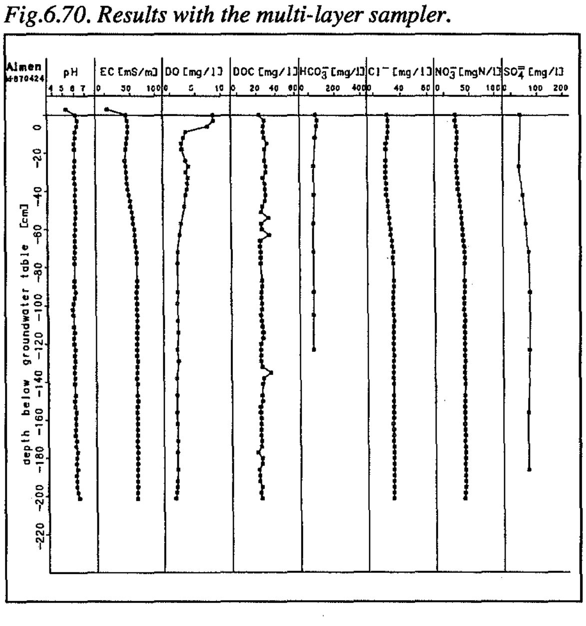


Fig.6.69. N concentrations in shallow groundwater ($mg{\cdot}l^{-1}$ as N).

deeper screens have been indicated in *Fig.6.71.* No conclusions can be drawn, because remarkedly , the nitrate concentrations of the deeper water in 1988 roughly correspond to those in the shallow groundwater, showing almost no reduction, whereas one year before, the nitrate concentrations appeared to be heavily reduced. The explanation of this phenomenon may partly be that the local situation indicated a varying pattern of vertical flow components. The upward seepage to the Berkel valley may be strong during wet periods, but much weaker in dry periods, when a downward flow prevails. A full explanation would require additional information not being available.

Fig.6.70. Results with the multi-layer sampler.



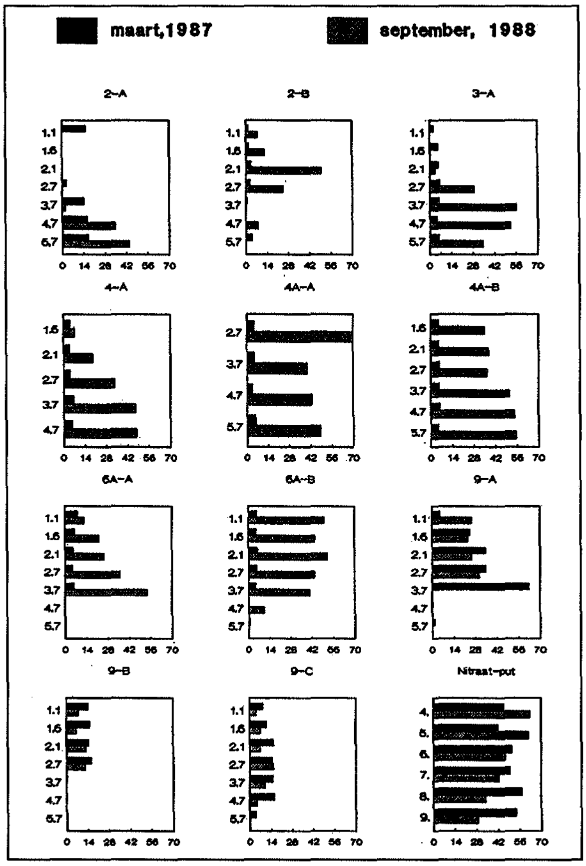


Fig.6.71. N concentrations in deeper groundwater ($mg{\cdot}l^{-1}$ as N) of the Almen farm.

6.3.5. The Neede test farm

6.3.5.1. Situation and investigations

The parcels of the Neede test farm (*Fig.6.72*) are scattered around the hamlet, Noorddijk. The northern parcel is situated on the flank of the Neederberg, a low ice-pushed hill. There, coarse gravels can be found in the soil, being remnants of a washing out after the ice left, but also clay bodies, which were removed from their original position. Topsoils were initiated by bringing in manure to fertilize the soil. The Neederberg itself, with an elevation of some 10 m above the surroundings, has now been planted with a mixed forest. An interesting feature is the presence of an iron foundry near the northern parcel which, in former times, was used for the fabrication of cast iron from the locally available bog ore. The parcel near the farmyard has an 'enk' soil, later levelled down and reworked. In 1850 (*Fig.6.73*), already much of the land was being used for agriculture.

The subsurface of the Neederberg consists of older sediments, including Tertiary clay layers, pushed by glaciers during the Saalian period. The areas west of it

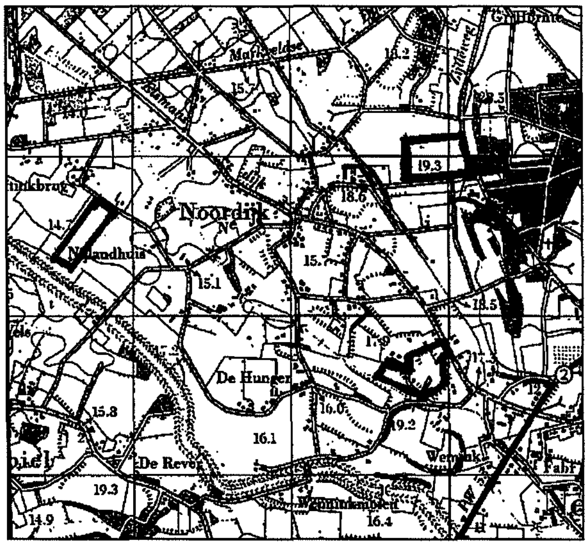


Fig.6.72. Situation of the Neede test farm.

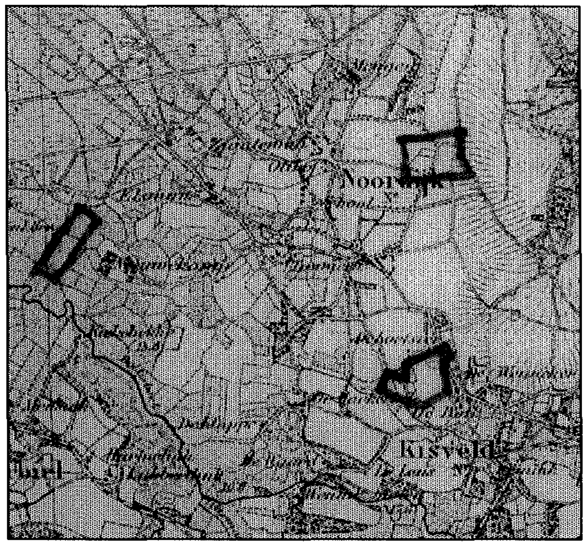


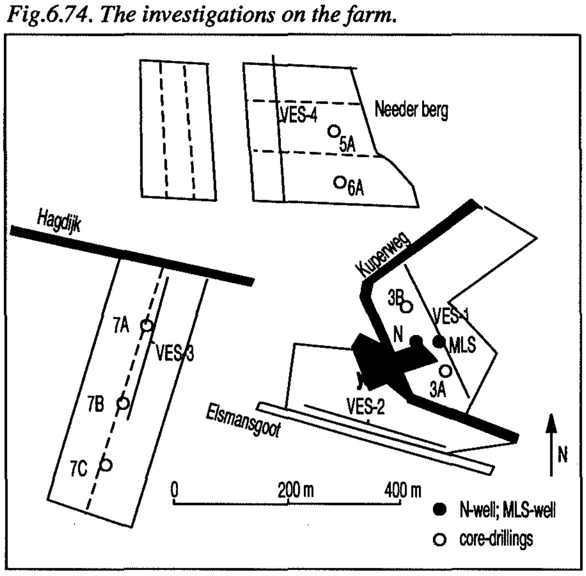
Fig.6.73. Topographical map of 1850.

are underlaid by former glacial valleys, filled in by fluvio-periglacial sediments of the Drenthe Formation. The sediments of this formation may have a variable composition, ranging from loam layers to relatively coarse sand layers. The uppermost layers belong to the Twente Formation, consisting of fluviatile and eolian sediments, deposited during the Weichselian cold period. These layers consist, in general, of fine sandy and loamy elements. Underneath the former glacial valleys, sandy sediments may be present, which form part of older fluviatile Pleistocene formations. These layers rest on clayey sediments of a Tertiary age, which are thick and practically impermeable.

The investigations on the farm (*Fig.6.74*) consisted of a soil survey by Stiboka, based on 120 boreholes. The deeper soil was investigated by means of four VES, a full coverage by EM-31 data, the drilling of 7 cored drillings to a depth of 8 m, in which observation screens have been installed, and the installation of a cable-tool drilling, with observation screens. Near the farmyard a multi-layer sampler arrangment was installed and sampled.

The farmyard is located in a stream valley with a soil containing organic material. The landscape is the half-open land with many trees, being characteristic for the eastern part of the province of Gelderland; a typical element is the corn-mill on top of the Neederberg, visible over a long distance. The most westernly parcel is situated in the broad valley of the Bolksbeek (*Fig.6.75*) with loamy sediments, locally containing bog ore. The groundwater table is relatively shallow in the valley.

Fig.6.74. The investigations on the farm.



6.3.4.2. Geohydrological structure

The sedimentology of the cores from the suction drillings indicated that the shallow layers consist of a sequence of aquatic and eolian sediments (Kerkhof, 1987). The deepest layers, at a depth of 5 to 8 m, contain predominantly fluviatile sediments; intermediate layers are dominated by eolian deposits and in the uppermost layers both type of depositions have occurred. The full set of layers consists of fine sands with few organic components. Also, in the fluviatile sediments, the influence of reworked cover sands can be recognized. Near the Neederberg, the suction drillings had to pass through clay layers, which could not be sampled, but which probably are of a Tertiary origin and washed from the hill. In the Bolksbeek valley, fluviatile deposits are present over the whole investigated depth.

Fig.6.75. The western parcel in the stream valley.

The subsurface was investigated by means of four VES, which did not indicate many differences. The interpretation of VES-1 to VES-4 is shown in *Figs.6.76* to *6.79*. The layers above a depth of 2 m form the unsaturated zone, which consists of sandy layers. The layers to a depth of 10 m represent the sandy layers, studied by sedimentological methods. Although the resistance is low, the layer should be sandy because the groundwater has a high average conductivity of EC=93 $mS{\cdot}m^{-1}$. A loamy layer is present at a depth of approximately 20 m. This loamy layer probably forms the base of sandy fluvio-periglacial sediments. Below a depth of 20 m, Pleistocene sediments constitute the deep subaquifer, which has its base at a depth of 40 to 50 m where clay layers are interpreted, presumably of a Tertiary age and acting as the hydraulic base of the aquifer system above it.

The shallow subsurface was surveyed with the EM-31 (*Fig.6.80*). The difference between 'enk' soils and stream valley soils results in EM-31 values lower than 7 $mS{\cdot}m^{-1}$ at the enk. The local variation at the parcel on the flank of the Neederberg will be expressed by the presence of clayey components. The values of more than 8 $mS{\cdot}m^{-1}$ at the Bolksbeek valley are determined by the presence of loamy sediments, but also by the shallow depth of the groundwater table.

As it may be assumed that the loam layers at a depth of 20 m will mostly exert a limited hydraulic resistance, the whole system to the depth of 50 m forms one single aquifer. The geohydrological structure of the subsurface has been summarized in *Fig.6.81*.

No isohypses have been determined on the basis of water levels measured in the farm parcels. However, the flow patterns will follow the regional flow, which is roughly from south-east to north-west. Only in the screens of the N well above a depth of 10 m, were tritium levels determined (*Fig.6.82*). The interpretation, assuming that D=45 m, yields:

f= 1.18 (regional factor);

I/p= 0.96 $m{\cdot}a^{-1}$ and I= 335 $mm{\cdot}a^{-1}$ at p=0.35.

The regional factor corresponds to the expected value (1.17). Groundwater recharge is equal to the local rainfall excess.

6.3.4.3. *Environmental implications*

Nitrate concentrations in the uppermost saturated groundwater, taken from the screens of the shallow boreholes and represented in *Fig.6.83* show a large variation. The variation corresponds to differences in soil types and in groundwater depths at the farm. The average annual application of nitrogen compounds to the farmland of the Neede test farm in the years before the investigations totalled 740 $kg{\cdot}ha^{-1}$, divided in 508 $kg{\cdot}ha^{-1}$ as fertilizer; 219 $kg{\cdot}ha^{-1}$ as manure slurry and 13 $kg{\cdot}ha^{-1}$ as field manure. The average concentration of nitrate in the shallow groundwater is 44 $mg{\cdot}l^{-1}$ (as N), representing a total of 59 observations. At an estimated groundwater recharge of 335 $mm{\cdot}a^{-1}$, it can be computed that the average annual leaching is 147 $kg{\cdot}ha^{-1}$, representing 20% of the total dose. The leaching of nitrogen compounds, estimated

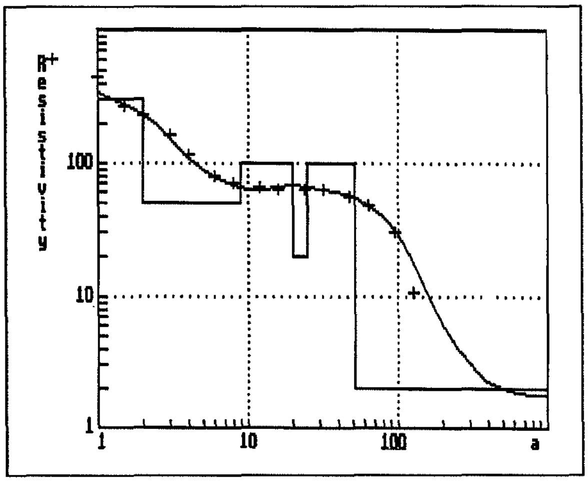


Fig.6.76. VES Neede-1.

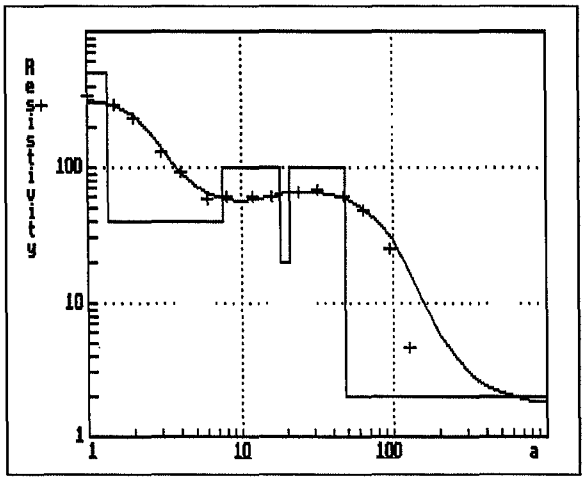


Fig.6.77. VES Neede-2.

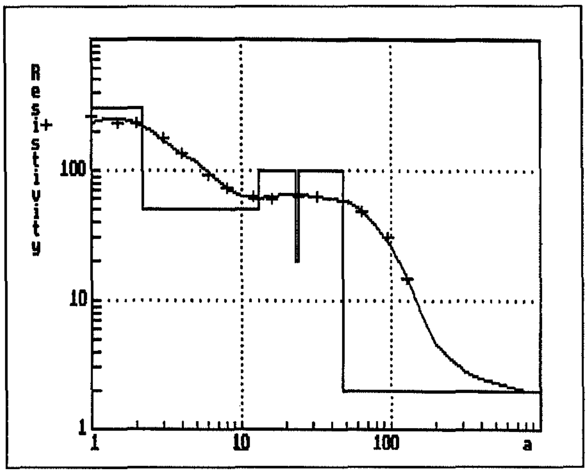


Fig.6.78. VES Neede-3.

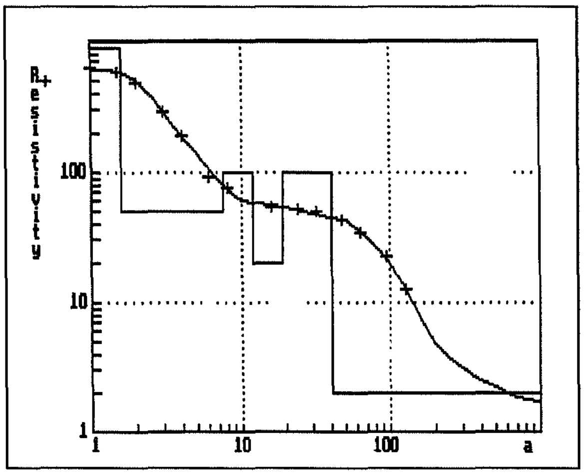


Fig.6.79. VES Neede-4.

Fig.6.80. EM-31 values ($mS{\cdot}m^{-1}$).

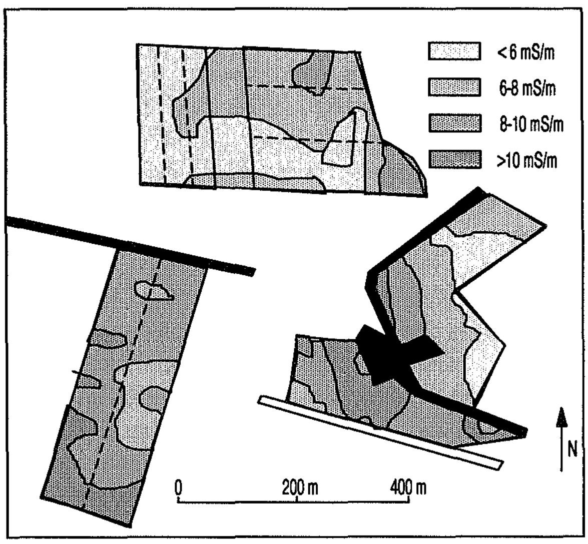
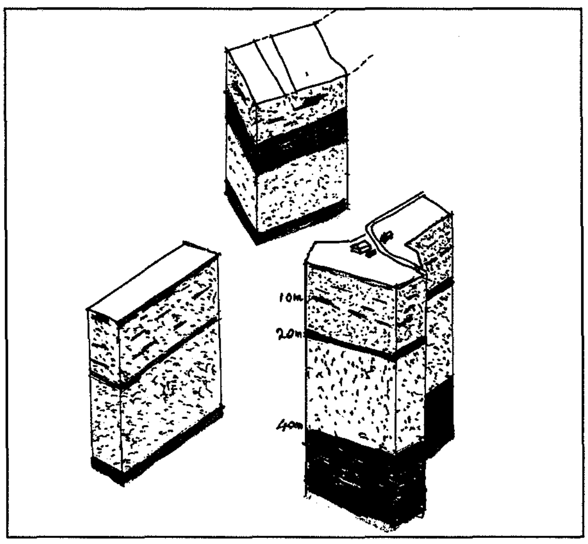


Fig.6.81. Soil structure.



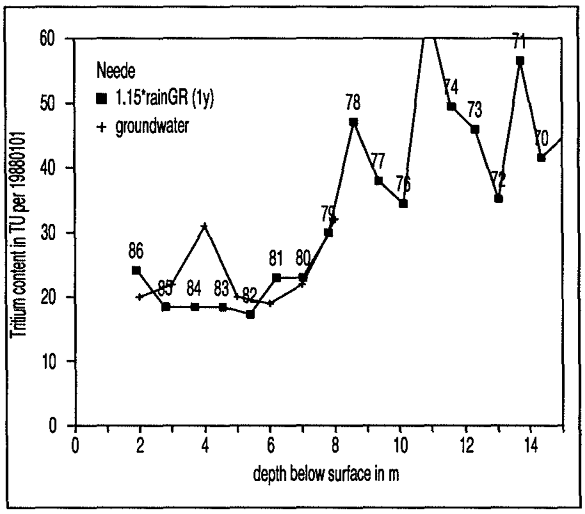
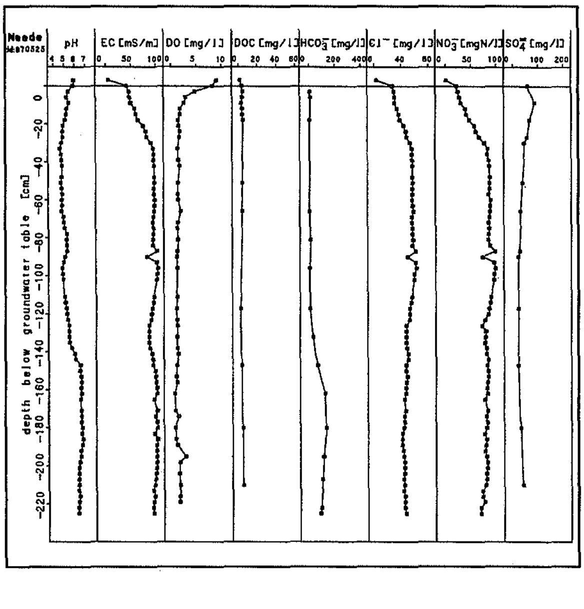


Fig.6.82. ³H level of N well.

from the NLOAD model, constitutes 14% of the dose at land surface. The observed leaching of nitrogen is larger than the predicted values.

The multi-layer sampler observations executed at the Neede test farm, represented in *Fig.6.84*, indicate nearly no fluctuations in the measured concentrations versus depth, except for the upper 30 cm, with exceptionally low values of all concentrations. This phenomenon will be further discussed along with re-

Fig.6.84. Results with the multi-layer sampler.



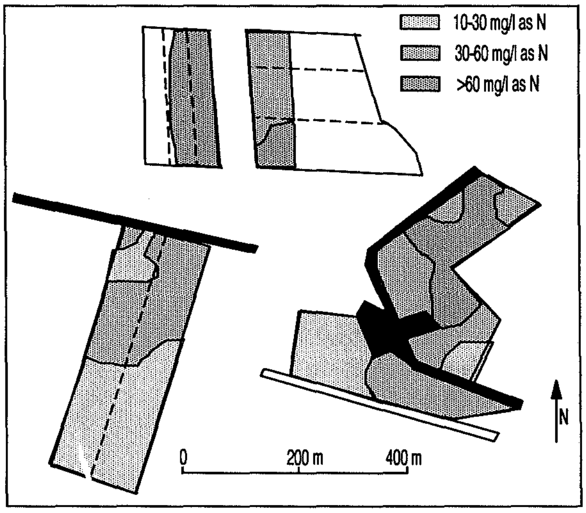


Fig.6.83.N concentrations in shallow groundwater ($mg{\cdot}l^{-1}$ as N).

sults obtained from the Moergestel test farm in the southern sand district, where the same type of deviating values was observed. The deeper concentrations correspond to the values measured in the nearby shallow groundwater, indicating the effect of mixing on a yearly basis in the unsaturated zone.

The observed nitrate concentrations in samples from deeper screens are represented in *Fig.6.85*. Based on the hydrological investigations, it is possible to esti-

Fig.6.85. N concentrations in deeper groundwater ($mg{\cdot}l^{-1}$ as N) of the Neede farm.

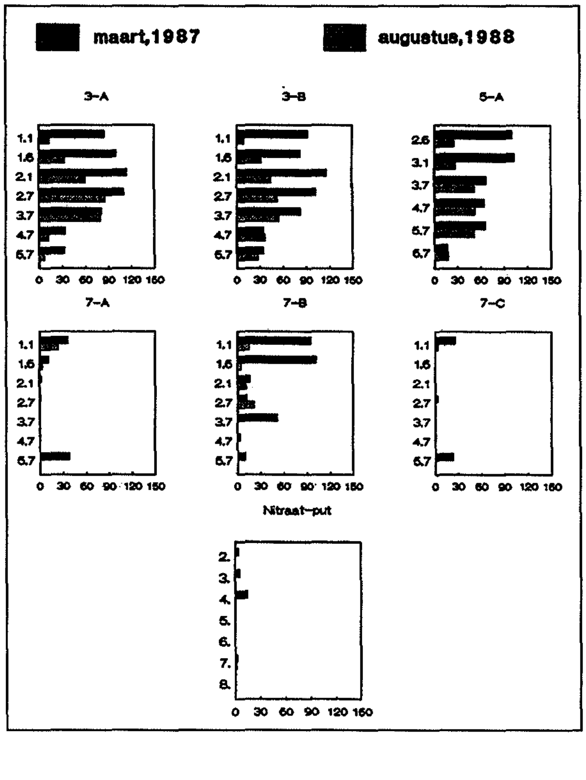


Table 6.9. Tritium levels in LMG wells in North Overijssel (1982-83) and an interpretation

LMG	Location	Landuse	1-83 TU	3-83 TU	3-82 TU	$I/p_{avg.}$ $m \cdot a^{-1}$	$I_{avg.}$ $mm \cdot a^{-1}$
194	kampen	built-up	49	74	83	1.13	395
196	eng.werk	unknown	61	42	31	0.77	268
197	zwolle	built-up	43	37	43	1.04	365
198	stjanskl.	unknown	55	48	46	1.04	364
199	rouveen	grass	48	1	1	0.94	328
200	staphorst	built-up	55	1	1	0.81	282
201	punthorst	forest	78	94	45	1.03	359
202	dalfsen	grass	63	1	1	0.67	235
204	witharen	forest	99	1	5	0.75	261
205	dedemsv.	grass	80	1	1	0.57	200

the hydrological investigations, it is possible to estimate the place of recharge and the travel times. Hence, a comparison of the values observed in the uppermost saturated groundwater and the values measured in deeper screens is possible. The conclusion is that:

50% of the deep observations correspond to shallow values;
25% of the observations indicate a reduction of roughly 50%;
25% of the observations indicate a reduction of more than 80%.

In general, it can be concluded that the rate of reduction within the saturated groundwater is less than 50%. Examples showing a strong nitrate reduction in the saturated groundwater are all situated in the Bolksbeek valley. The genesis of the shallow sediments, which are largely deposited by streams and which probably contain organic matter, will be one of the factors involved.

6.3.6. Tritium data of Groundwater Monitoring Stations

6.3.6.1. North Overijssel

The northwest part of the province of Overijssel consists of an area with many lakes and with considerable peat layers in the shallow soil, except for small zones on the fringes of the Drenthe Plateau. West of the peat zone, a more sandy area begins, where the soil only incidentally contains peat. On the east side of the region a raised bog was present, which was exploited in the last century. The central axis of the area is formed by the canal, Dedemsvaart, which made the transport of peat to the consumers possible. The canal is now reduced to a broad draining ditch. The land is flat and open and regularly parcelled; it does not contain many settlements. More towards the fringes, groups of tall trees are scattered over the land. In the subsurface, a buried glacial valley is present. The clayey deposits at the bottom will, in general, not be fully impermeable and for that reason it is assumed that the base of the aquifer is at a depth of D=100 m. The measured tritium levels in the LMG wells are represented in *Table 6.9*, together with an interpretation, which yields as average results (at p=0.35):

forest:	n=2;	$I/p=0.89\ m \cdot a^{-1}$;	$I=310\ mm \cdot a^{-1}$;
built-up:	n=2;	$I/p=0.93\ m \cdot a^{-1}$;	$I=325\ mm \cdot a^{-1}$;
grass:	n=3;	$I/p=0.73\ m \cdot a^{-1}$;	$I=254\ mm \cdot a^{-1}$

6.3.6.2. Salland

The Salland region is an agricultural area with predominantly a sandy soil. The land is drained by a large number of small streams, which discharge their water in a collector stream, flowing parallel to the river; they only converge near the city of Zwolle. Before the introduction of fertilizer, many wastelands had a heather vegetation, but since then the land has been reclaimed for animal husbandry. The land use at the moment is permanent pasture with scattered maize parcels and a few forests of a limited area. On the east side, the hills of the Overijsselse Heuvelrug dominate the landscape. Large parts of these hills are nature reserves.

The subsurface of the whole area between the Veluwe in the west and the hills of the Overijsselse Heuvelrug contains a buried glacial valley. In its centre, the base of the valley is more than 100 m below present land surface. The filling in of the valley con-

Table 6.10.. Tritium levels in LMG wells of West Overijssel in Salland (1982-83) and an interpretation

LMG	Location	Landuse	1-83 TU	3-83 TU	3-82 TU	$I/p_{avg.}$ $m \cdot a^{-1}$	$I_{avg.}$ $mm \cdot a^{-1}$
209	windesh.	grass	51	1	1	1.04	364
210	wijhe	built-up	25	17	1	1.07	375
211	rechteren	forest	58	1	1	0.80	281
212	raalte	grass	58	1	und.	0.84	294
213	eikelhof	grass	57	27	18	1.11	388
214	deventer	built-up	62	19	18	0.86	301
215	dijkerh.	grass	45	6	8	0.97	339
216	nijverdal	forest	55	1	1	0.97	340
217	lemele	forest	42	86	und.	1.22	426

sists of thick clay layers at the deepest part; the clayey components become less prominent near the fringes. On the fringes of the valley, also the deeper sandy layers form part of the phreatic aquifer. The average depth of the first aquifer is taken to be D=50 m, leading to the measured tritium levels represented in *Table 6.10*, where the interpretation is also given. Average values for the different types of land use are:

forest:	n=3;	$I/p=1.00\ m \cdot a^{-1}$;	$I=349\ mm \cdot a^{-1}$;
built-up:	n=2;	$I/p=0.97\ m \cdot a^{-1}$;	$I=338\ mm \cdot a^{-1}$;
grass:	n=3;	$I/p=1.00\ m \cdot a^{-1}$;	$I=348\ mm \cdot a^{-1}$.

6.3.6.3. Central Overijssel

The landscape in the central part of the province of Overijssel is variable. The hills of the Overijsselse Heuvelrug border the area in the west. In the east, the slightly elevated Twente region provides a water divide. The land is drained by the Regge with its subsidiaries. The valleys were originally swampy, so that in the northern part of the region a vast peat bog could develop, which was largely excavated in the last century. In former times, the residential areas and the arable land were situated at the relatively higher parts at the flanks of the hills and in Twente. The low lands were used as meadows or remained wastelands. At present, much of the land has been reclaimed for animal husbandry, although some small mixed and deciduous forests are dispersed over the region. The land of the former peat bog is open and regularly parcelled.

The subsurface of the central part of the area contains a buried glacial valley, which has been filled in by fine, but mostly sandy deposits. The interpretation of the tritium levels, observed in the LMG wells has been based on D=40m. Measured values and an interpretation are given in *Table 6.11.*
An average value of groundwater recharge (p=0.35) is:

grass: n=3; $I/p=0.92\ m \cdot a^{-1}$; $I=322\ mm \cdot a^{-1}$

6.3.6.4. Twente

The region of Twente has been inhabitated since Roman times. It has a varied topography. The relatively flat west part is a region of the East-Netherlands Plateau, where Tertiary layers are found at shallow depths. The soil is dissected by minor glacial valleys, now filled in, but often still with a small stream in the

Table 6.11. Tritium levels in LMG wells in central Overijssel (1982-83) and an interpretation

LMG	Location	Landuse	1-83 TU	3-83 TU	3-82 TU	$I/p_{avg.}$ $m \cdot a^{-1}$	$I_{avg.}$ $mm \cdot a^{-1}$
206	den ham	grass	7	5	undet.	undet.	undet.
207	kloosterh	arable	55	1	1	1.10	387
216	nijverd.	forest	24	1	1	undet.	undet.
218	hellend.	grass	59	5	undet.	0.96	336
226	markelo	grass	46	1	undet.	0.88	308

Table 6.12. Tritium levels in LMG wells in east Overijssel, Twente (1982-83) and an interpretation

LMG	Location	Landuse	1-83 TU	3-83 TU	3-82 TU	$I/p_{avg.}$ $m \cdot a^{-1}$	$I_{avg.}$ $mm \cdot a^{-1}$
220	vasse	grass	59	5	undet.	1.06	318
221	almelo	built-up	136	1	undet.	0.45	159
222	weerselo	grass	18	1	undet.	undet.	undet.
223	hengelo	arable	59	25	undet.	0.83	289
224	enschede	forest	54	1	undet.	1.06	371
225	denekamp	built-up	40	1	undet.	1.26	440
226	markelo	grass	46	1	undet.	0.89	313
227	de lutte	forest	46	1	undet.	1.19	417

centre. Near Oldenzaal, the Tertiary clay layers were pushed into a push-ridge by glacial glaciers; the soil is clayey and no aquifers are present. The most eastern part contains the Dinkel valley, where the subsurface again consists of sandy deposits to a depth of roughly 40 m below surface.

Land use in Twente consists mainly of permanent pastures used for normal animal husbandry, formerly in combination with arable land. At present, the arable land is mostly used for maize cultivation to provide cattle fodder. Many small deciduous forests make this country a pleasant sight. In the last century, Twente became the site of an important textile and steel industry, which nowadays is in decline.

The complicated subsurface is first approached by assuming that D=25 m. However, a detailed interpretation of the measured tritium levels in the LMG wells (*Table 6.12*) would require a detailed consideration of the local situation. The following average values result from the interpretation:

grass:	n=2;	$I/p=0.98\ m \cdot a^{-1}$;	$I=316\ mm \cdot a^{-1}$
forest	n=2;	$I/p=1.13\ m \cdot a^{-1}$;	$I=394\ mm \cdot a^{-1}$

6.3.6.5 Achterhoek

The eastern part of the province of Gelderland, called the Achterhoek, is a flat region with a sandy soil, where large parts of the rainfall excess are discharged by groundwater. The groundwater is flowing to a regular network of local streams and as a regional groundwater flow in a mainly westward direction to the River IJssel valley. Originally, the land was used by farmers living in the larger villages, but also in smaller hamlets or on single farms, each provided with a so-called 'enk', where the arable land was fertilized by dung of cattle grazing in the vast wastelands mainly having a heather vegetation. The stream valleys contained meadows, used as hayfields. Reclamation of almost all the wastelands ('markelanden') had already started more than 150 years ago, providing partly permanent pastures and partly arable land. At present, much maize is grown on the former arable land, but also some of the pasture has turned into maize fields. Cover sand ridges often were planted with pine forests and also in other parts of the area small dispersed forests, sometimes of a mixed type, are present. Generally, the streams flow roughly parallel to each other at a distance of 5 km in a SE-NW direction.

The area contains one single unconfined aquifer with a transmissivity of, on the average, 2000 $m^2 \cdot day^{-1}$ (Ernst et al., 1970), except in the easternmost part. The average thickness of the aquifer is 50 m, but large deviations occur. Near the River IJssel, the existence of a former glacial valley has resulted in depths of about 70 m of the sandy layers. Presumably, the groundwater flow in between the streams may be compared to the scheme of flow in a single aquifer underneath a circular area, implying that the equation derived for that situation holds. In the vicinity of a stream valley the pattern is more complicated, as it is also determined by upward vertical velocities. The age distribution in the aquifer below the stream zones will be complicated. The situation will lead to the presence of both relatively old and young water.

Both LMG and PMG wells were sampled in order to determine the groundwater tritium levels. The results and an interpretation are presented in *Tables 6.13* and *6.14*. Only the samples from wells in the region with sandy layers of a significant thickness are interpreted and not the wells in the subsurface of the elevated terrace in the east. The results for situations with the same type of land use can be averaged. For East-Gelderland, the average downward infiltration rates

Table 6.13.. Tritium levels in LMG wells in the Achterhoek (1982-84) and an interpretation.

LMG	Location	Landuse	1-84 TU	3-84 TU	3-82 TU	$I/p_{avg.}$ $m{\cdot}a^{-1}$	$I_{avg.}$ $mm{\cdot}a^{-1}$
1	gorssel	forest	56	26	7	0.90	317
2	harfsen	grass	24	<5	6	0.85	288
3	laren	forest	45	<5	<5	0.85	298
4	warnsv.	grass	47	39	66	1.32	463
5	keyenb.	ar.land	63	23	21	0.89	310
6	veldhoek	forest	62	28	24	0.96	338
7	vorden	forest	83	23	21	0.89	313
8	ruurlo	built-up	55	36	57	1.42	499
9	eibergen	grass	65	28	24	0.95	333
10	lievelde	grass	34	<5	<5	1.00	350
12	ijzerlo	grass	79	38	34	0.87	305
13	heelweg	grass	15	7	32	1.14	399
14	gaanderen	grass	35	<5	<5	undet.	undet.
15	lengel	ar.land	65	23	29	1.13	394
16	hummelo	ar.land	84	13	13	1.05	367
17	didam	built-up	33	41	63	0.94	329
18	angerlo	unknown	34	43	45	1.11	390
20	noorddijk	grass	56	<5	<5	0.91	318

are:

grassland :	n=10;	$I/p_{avg.}$=0.91 $m{\cdot}a^{-1}$;	$I_{avg.}$=320 $mm{\cdot}a^{-1}$;
arable land:	n=6;	$I/p_{avg.}$=0.91 $m{\cdot}a^{-1}$;	$I_{avg.}$=317 $mm{\cdot}a^{-1}$;
built-up area:	n=5;	$I/p_{avg.}$=1.07 $m{\cdot}a^{-1}$;	$I_{avg.}$=373 $mm{\cdot}a^{-1}$;
forest areas:	n=8;	$I/p_{avg.}$=0.82 $m{\cdot}a^{-1}$;	$I_{avg.}$=285 $mm{\cdot}a^{-1}$;

The values derived for built-up areas are strongly varying.

Table 6.14.. Tritium levels in PMG wells in the Achterhoek (1990) and an interpretation.

PMG	Location	Landuse	1-90 TU	2-90 TU	3-90 TU	$I/p_{avg.}$ $m{\cdot}a^{-1}$	$I_{avg.}$ $mm{\cdot}a^{-1}$
1010	almen	forest	52	66	27	0.79	277
1013	veldhoek	grass	20	44	27	0.83	292
1015	zelhem	ar.land	25	39	27	0.90	314
1016	lintelo	ar.land	25	42	37	0.95	334
1019	lochem	built-up	16	38	49	0.90	17
1020	gaanderen	built-up	31	33	36	1.31	460
1021	doetinch.	built-up	15	43	34	0.74	259
1008	langerak	forest	44	48	und.	0.50	175
1011	de meene	forest	20	48	und.	0.67	233
1012	kilder	grass	10	20	und.	0.72	251
1017	steend.	built-up	24	und.	9	2.00	699
1018	halle	grass	14	und.	25	0.57	196
1022	loerbeek	forest	44	und.	<5	0.95	331
1023	stokkum	ar.land	65	23	29	0.53	185

6.3.7. Summary of results

Based on the tritium data, the downward percolation on the test farms and near the LMG and PMG wells was estimated. The values represent long-term averages, resulting in long-term averages of the groundwater recharge which can be related to the rainfall excess. The average water balance can be elaborated in the form:

$$I= P-E_p-R+dE \quad \text{and} \quad R-dE=P-E_p-I,$$

with: I= the downward percolation ($mm{\cdot}a^{-1}$);
P= long-term average precipitation ($mm{\cdot}a^{-1}$);
R= average surficial runoff ($mm{\cdot}a^{-1}$);
E_p= potential evapotranspiration for a vegetation ($mm{\cdot}a^{-1}$);
dE= the sum of the amount of sprinkling water and the reduction in evapo-transpiration, due to water shortages in the soil in dry periods ($mm{\cdot}a^{-1}$).

Values of P and E_p can be determined, based on the estimates in Chapter 2 and I was calculated from tritium data, implying that a value for (R-dE) can be estimated. An elaboration for the determined values of I in the various subregions yields:

North Overijssel:	
LMG wells; grassland:	$P-E_p-I= 790-530-255= \ 5\ mm{\cdot}a^{-1}$;
LMG wells; forest:	$P-E_p-I= 790-605-310=-120\ mm{\cdot}a^{-1}$;
West Overijssel, Salland:	
Holten test farm; grassland:	$P-E_p-I= 780-530-325=-\ 75\ mm{\cdot}a^{-1}$;
LMG wells; grassland:	$P-E_p-I= 790-530-350=-\ 90\ mm{\cdot}a^{-1}$;
LMG wells; forest:	$P-E_p-I= 790-600-350=-160\ mm{\cdot}a^{-1}$;
Central Overijssel:	
LMG wells; grassland:	$P-E_p-I= 780-525-320=-\ 65\ mm{\cdot}a^{-1}$;
East Overijssel, Twente:	
LMG wells; grassland:	$P-E_p-I= 760-525-315=-\ 80\ mm{\cdot}a^{-1}$;
LMG wells; forest:	$P-E_p-I= 760-525-395=-160\ mm{\cdot}a^{-1}$.
Achterhoek:	
Almen test farm; grassland:	$P-E_p-I= 800-540-280=-\ 20\ mm{\cdot}a^{-1}$;
Neede test farm; grassland:	$P-E_p-I= 750-535-335=-120\ mm{\cdot}a^{-1}$;
LMG wells; grassland:	$P-E_p-I= 765-540-320=-\ 95\ mm{\cdot}a^{-1}$;
LMG wells; arable land:	$P-E_p-I= 765-485-320=-\ 40\ mm{\cdot}a^{-1}$;
LMG wells; forest:	$P-E_p-I= 765-605-285=-125\ mm{\cdot}a^{-1}$.

It can be concluded from the above review that:

1. The value (R-dE) is negative in many cases. The sum of a reduction in evapotranspiration and the amount of sprinkling water has the order of 70 $mm{\cdot}a^{-1}$ for grassland, if it is assumed that the surficial discharge is absent at the investigated locations (which generally will be the case).
2. The factor (R-dE) assumes relatively high negative values for forest areas, possibly indicating that the estimate is inaccurate. The number of forest locations is small in each region, which contributes to the inaccuracy of the determination. But maybe the most important reason is the location of the monitoring wells, such that also the recharge in open spaces determines the local value of groundwater recharge.
3. In general, the estimated values of groundwater recharge, based on tritium data, correspond to the results of long-range regional water balances.

6.4. The central sand district

6.4.1. Geography and landscape

The central sand district (*Fig.6.86*), covering the western part of the province of Gelderland, the eastern part of Utrecht and the Gooi region in North Holland is characterized by long ridges of hills and broad valleys in between. The ridges were pushed by large glaciers during the Saalian Glaciation in the Pleistocene Age. The Veluwe hills are a collection of several ice-pushed ridges. The Utrechtse Heuvelrug consists of two elongated ridges, running roughly from south-east to north-west. More to the north, the Gooi region is a continuation of the Utrecht ridges. The valleys are the remnants of glacial basins, which are still low areas, receiving the excess (seepage) water from the adjacent hills. From east to west, the following regions are distinguished:

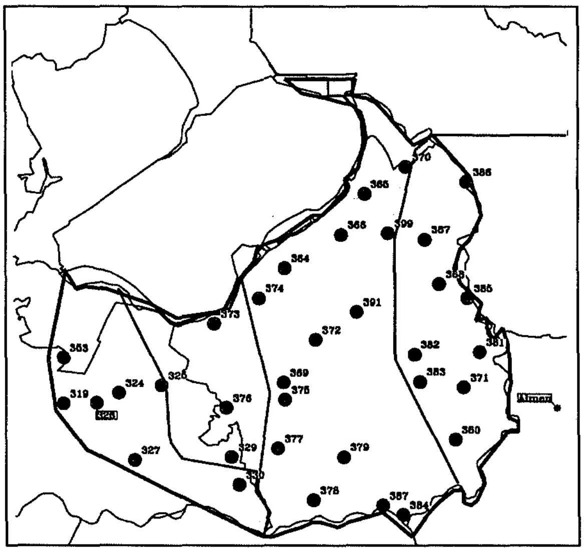


Fig.6.86. The central sand district with the location of LMG wells.

1. The IJssel Valley
   The Gelders IJssel Valley is bordered in the east by the River IJssel, a Rhine branch and in the west by the Veluwe hills. The area has a concave form, the drainage channels flow parallel to the river and only discharge in the IJssel at the north. The subsurface is sandy to a depth of roughly 40 m and the upward seepage of Veluwe groundwater is limited, implying that most of the area is relatively dry, although some zones exist where swampy conditions prevailed in the past. The land is largely used for animal husbandry.
2. The Veluwe hills
   The highest parts of the Veluwe hills were never reclaimed for agriculture because of infertile sandy soils and deep water tables. Large parts were used as hunting grounds. The hills remained wasteland, with a heather and forest vegetation. In many places, bare lands with moving small dunes occurred in the recent past. Much of the open land was converted into pine forests in the past 150 years; these are now important nature reserves. The flanks of the hills presented more favourable circumstances for agriculture because groundwater occurs at attainable depths. A ring of villages based on agriculture and animal husbandry developed around the Veluwe hills. Small-scale industries were already developed at an early date in the villages on the east and south flanks.
3. Gelderse Vallei
   The Gelderse Vallei receives seepage water from the hills on both sides. In the subsurface, a clay layer is present at shallow depths. The region was a predominantly wet and swampy area, drained by a large number of local streams. Only on the somewhat higher lands did villages develop. In the recent past, the streams were canalized and deepened, leading to a drainage of the land. An intensive animal husbandry was developed in the area.
4. Utrechtse Heuvelrug and Gooi
   On a smaller scale, the western hilly regions of the Utrechtse Heuvelrug and Gooi have the same features as the Veluwe hills. The higher areas are largely planted with pine trees and a row of villages has developed mainly at the southwest flank. The Gooi area is densely populated.

6.4.2. Hydrological situation

The hydrogeological structure of the central sand district (*Fig.6.87*) is dominated by glacial features. The hills are ice-pushed ridges with a sandy subsurface down to relatively great depths. In the central parts, no surface water discharges the rainfall excess; an important groundwater flow leaves the hilly regions in the direction of the surrounding valleys. The valleys are underlaid by glacial basins, which were scoured by the ice and which discharged melt water during the retreat of the Pleistocene glaciers. The filling-in of the deepest parts of the glacial basins occurred with fluvio-periglacial deposits, containing clayey and loamy sediments. In parts of the valleys, the groundwater in the deep aquifer is artesian, implying an upward seepage. In the IJssel valley, the basal clay layers of the former glacial valley are thick and almost fully impervious. The subsequent deposition consisted of coarse river sediments, implying the presence of a well-developed upper aquifer. The flu-

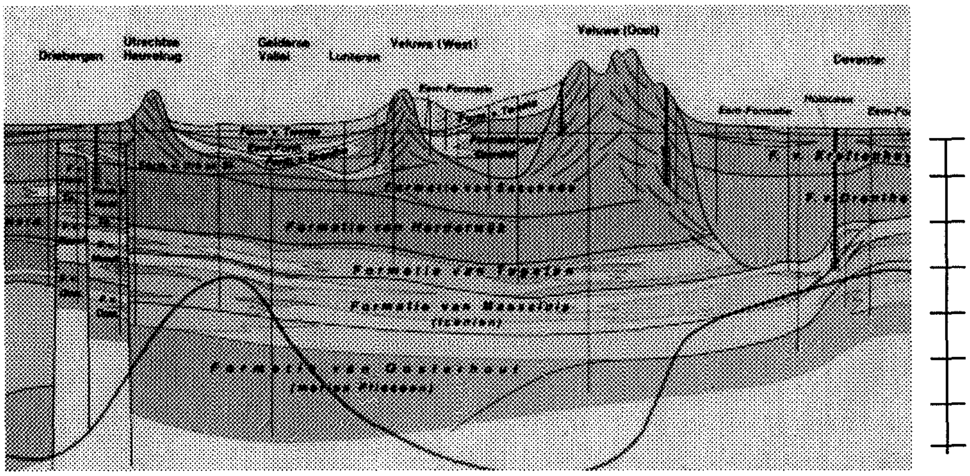


Fig.6.87. Hydrogeological cross-section according to Jelgersma (1977).

vio-periglacial layers in the glacial basin below the Gelderse Vallei do not fully confine the deeper aquifer. The later deposits contain marine sediments of the Eemian period, which exert a relatively high hydraulic resistance to vertical flow. The sandy sediments above the marine clay consist of fine sand, deposited by local streams and by aeolian transport during the Weichselian Glaciation.

Special attention is given to the features of the Veluwe 'sprengen', which are the means of drainage of considerable parts of Veluwe groundwater. As early as the Middle Ages, the groundwater resources on the east and south flanks of the hills were developed in the form of artificial springs (the sprengen), producing both clean water and energy in the form of hydropower, sustaining the local small-scale industry (paper and copper production). The industries are still present, but the sprengen have been abandoned for the energy supply; in a few cases the water is still used. The sprengen have various forms:

'Kop' sprengen (Moerman, 1934) can be found in the north-east Veluwe. The sprengen are fed by a small pond dug at a site suitable for the captation of groundwater. The south-eastern sprengen receive water from upstream branches where the groundwater is drained. The largest southern sprengen run parallel to a hill ridge and tap the groundwater by means of short draining lateral branches ('flank'sprengen). In the southern hills, some smaller sprengen captate perched groundwater tables. Most sprengen only drain the groundwater at upstream reaches; the lower courses merely transport the water to places where needed, the bed is sometimes lined with a loam layer. The main causes of an observed decrease in discharge of all sprengen are groundwater withdrawals and changes in vegetation of upstream areas, where heathlands have turned into pine forests, implying a reduction of groundwater recharge. The discharge of the sprengen is relatively constant with time (Kant, 1982). The groundwater flow situation is summarized in *Fig.6.88.*

Fig.6.88. Schematical representation of groundwater flow to sprengen in the east and south Veluwe

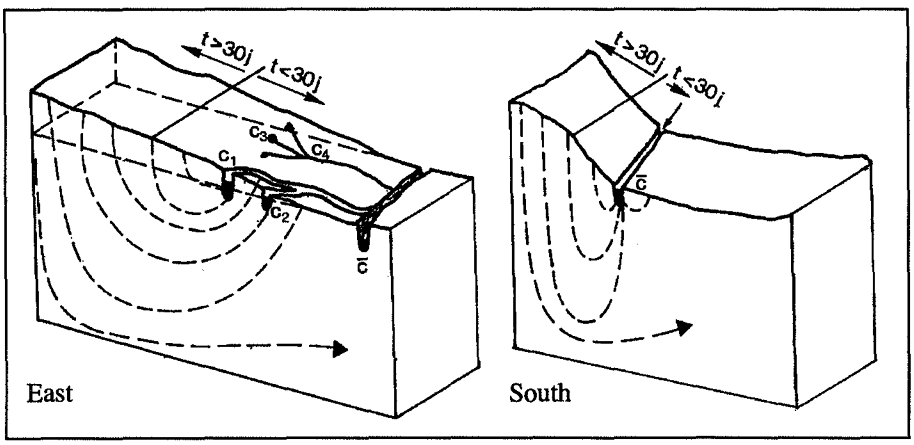


Table 6.15. Estimates of the spatial and temporal variations in the composition of precipitation in the Veluwe region; all concentrations in $mg \cdot l^{-1}$.

The columns represent various situations:

<1890: the average situation before 1890;
avg. 90-50: the average situation from 1890 to 1950;
avg. 50-80: the average situation from 1950 to 1980;
NW '80: the average situation at the north-west Veluwe in 1980;
SE '80: the average situation at the south-east Veluwe in 1980.

	<1890	avg.90-50	avg.50-80	NW '80	SE '80
Chloride(Cl^-)	3	3	3	4	2.5
Sulphate(SO_4^{2-})	3	4	7	6.5	6.5
Nitrogen(as N)	0.3	0.5	1	2	2
Calcium(Ca^{2+})	1.7	1.7	1.8	1.8	1.8
Magnesium(Mg^{2+})	0.4	0.4	0.4	0.5	0.3
Sodium(Na^+)	1.8	1.8	1.8	2.3	1.4
Potassium(K^+)	0.18	0.18	0.18	0.23	0.14

6.4.3.1. Scope of the field studies.

The sandy subsurface of the Veluwe contains an important reservoir of fresh groundwater recharged by rainfall. The groundwater quality is still good because the polluting effects of agriculture are absent and deeper layers are not yet affected by air pollution. The availability of good quality groundwater makes the Veluwe of great importance for the water supply of adjacent regions. But also, the ecological situation and its variation in the Veluwe area largely depend on the quantity and the quality of the groundwater.

The Veluwe hills represent the largest area of interconnected nature reserves in the Netherlands, a much valued feature in the densely populated country. Plant growth depends on quantity and quality of rainfall and has many features of an oligotrophic vegetation. At present, rainfall is contaminated by pollution (*Table 6.15*) and the vegetation is changing. Trees are becoming less viable and heathlands are turning into grasslands. The sprengen in the east and south flanks of the hills constitute specific elements of great natural value but are threatened in their existence by changes in the quantity and quality of the recharging water.

In general, the type of groundwater recharge in forest areas and other nature reserves is not exactly known. Most research in the past was directed to agricultural areas. Studies with regard to the quantity of recharge can support a better knowledge of the hydrological situation of natue reserves. Another three reasons make the area interesting for a thorough evaluation of the groundwater composition:

1. The vegetation of natural areas is changing; a changing groundwater composition is one of the factors implied.
2. The continuity of the drinking-water supply from groundwater depends on the future quality of its sources.
3. The effects of atmospheric deposition on (shallow) groundwater composition can be more easily investigated in areas where other side effects may be ignored.

In the following, some specific field investigations, aiming at a more profound knowledge of the factors determining quality and quantity of groundwater recharge in the Veluwe area will be discussed. The quality aspects of shallow groundwater constitute one of the subjects of study. Other investigations have concerned quantity and quality of the water discharged by the sprengen which represents groundwater of variable travel times in the subsurface. Quality and quantity of groundwater recharge are strongly related: The groundwater composition can indicate the amounts of recharge. The comparison between the composition of precipation, varying in time and space, and the resulting groundwater composition can provide estimates of the groundwater recharge in various situations.

6.4.3.2. Methods of investigation

The present study is based mainly on recent investigations by RIVM. The results are placed in the context of various other studies. A general description of the hydrological features of the area will provide the

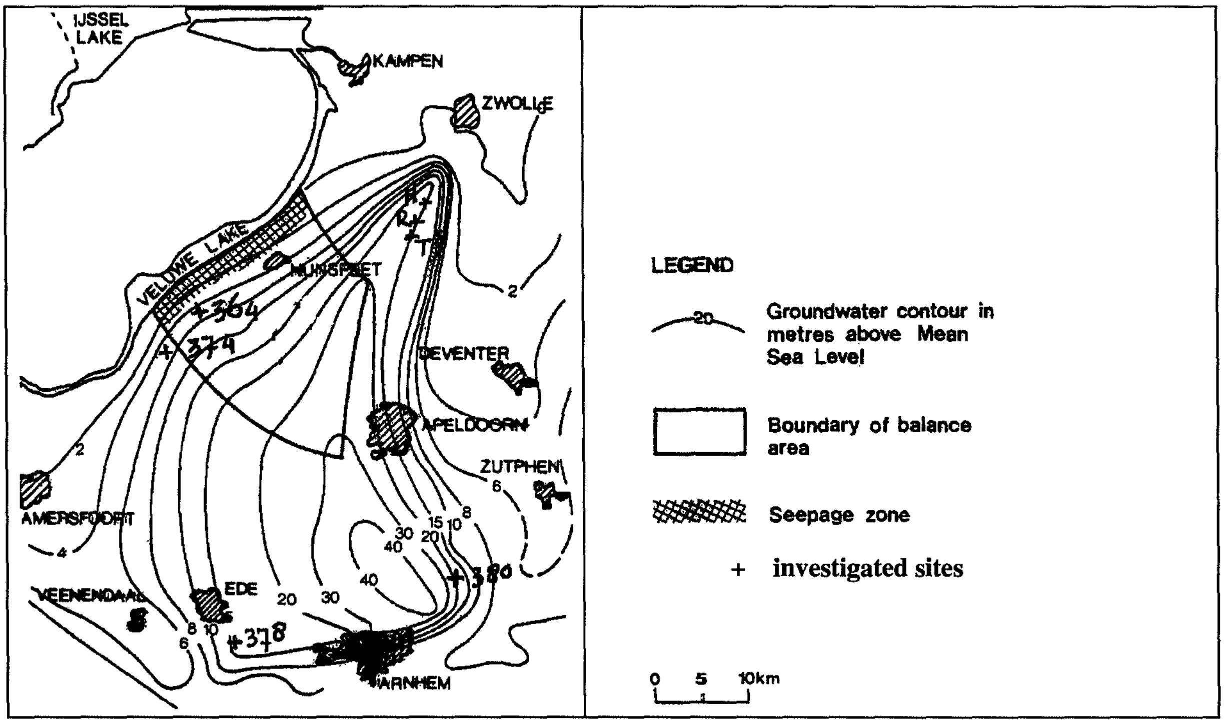


Fig.6.89. Isohypses of the Veluwe area and the situation of the investigated sites.

general framework, supported by a study concerning the water balance of the north-west part of the Veluwe. The investigations (*Fig.6.89*) consisted of: detailed investigations at specific locations, hydrological research on the Veluwe sprengen and groundwater recharge studies, based on the groundwater's composition.

A. Detailed investigations at specific locations

Local fieldwork was executed in the vicinity of the wells of the Groundwater Monitoring Network (LMG wells). Near these wells an extra well (N well) was drilled with the cable-tool method to a depth of 15 m below surface. The well was provided with small screens at intervals of 1 m. During the fieldwork, a varying number of manually drilled shallow boreholes, provided with screens on the top of the saturated groundwater, were temporarily installed in the surroundings. In an area of several hectares around the LMG well a few geo-electrical surface measurements (VES) were taken and the same area was covered by EM-31 measurements. The various screens were sampled and the water analyzed with regard to the major components of groundwater composition. At the N well, samples to determine the tritium level were also taken. The chemical analysis and the determination of the tritium level were done at the RIVM laboratories. During sampling and analyzing, the standard RIVM procedures were followed. The groundwater levels in the screens of the boreholes have been measured and the wells surveyed in order to compose groundwater isohypses, representing the local situation.

B. Hydrological research on the Veluwe sprengen

Research on the Veluwe sprengen also formed part of the above study of nitrogen in groundwater; the sprengen form the outcrop of Veluwe groundwater. The fieldwork has focused on the upstream reaches of the sprengen and the recharge areas. In *Fig.6.90* the locations of the various sprengen are given and the estimated situation of the recharge areas is indicated. The studies, carried out in June 1986, comprised the following elements for each location:

a. The discharge was determined by a salt balance method through a momentary salt injection (WMO) and the downstream measurement of the resulting electrical conductivity in the water. Measurements were done at points, where presumably, the seepage towards the sprengen had largely finished. The results of the discharge measurements are not very accurate, mainly because of the largely imperfect mixing between injection and measuring points. Nevertheless, the approximate amounts of the flow rates of the various sprengen were obtained. The resulting flow rates were used to estimate the location of the recharge areas by assuming a groundwater recharge of I=250 $mm{\cdot}a^{-1}$ (first estimate) and taking into account the isohypses and groundwater divides of *Fig.6.89*.
b. In the vicinity of each source a geophysical survey was carried out, consisting of one VES and,

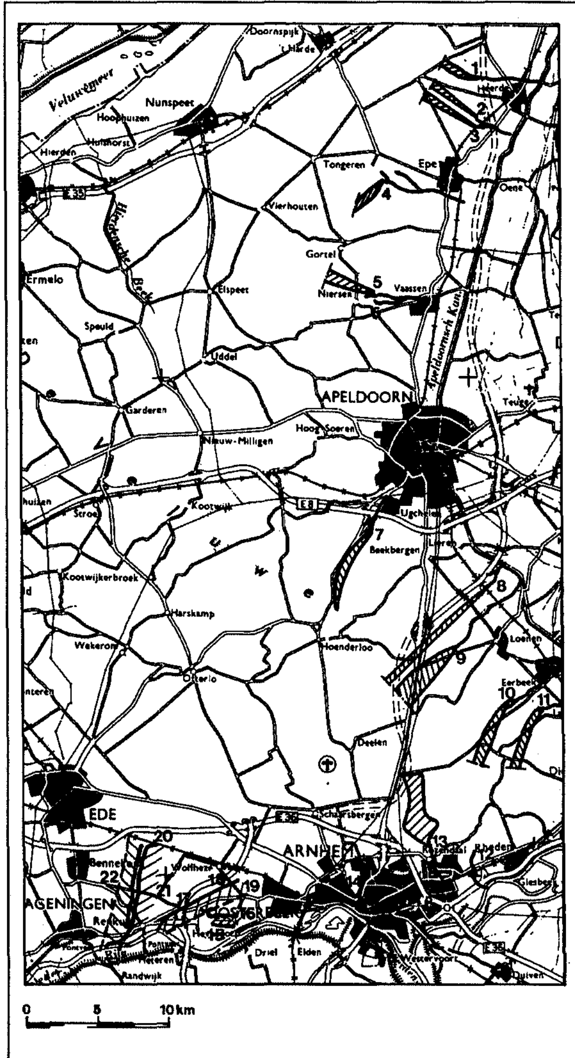


Fig.6.90. Situation of the sprengen and their catchment areas (the hatched areas).

where possible, EM-31 measurements. At places with deep groundwater levels, the soil resistance was too high to use the EM-31.

c. The water of the sprengen was sampled and analyzed for the major physical-chemical properties. The analyses of the water samples were carried out by students of the Geography Department of Utrecht University (RUU) by means of an auto-analyzer. The ^{18}O and the ^{3}H levels were determined on the same samples. The isotope determinations of the ^{18}O levels were done by Groningen University (CIO) and those of ^{3}H levels by RIVM.
d. The temperature of the water was recorded.
e. At some locations, a number of shallow boreholes were drilled to the top of the saturated groundwater during fieldwork in December 1986, with the aim of collecting samples from the groundwater, recharging the sprengen. The samples were chemically analyzed, again by students of RUU.
f. At one location twelve samples of groundwater were analyzed, both at the RIVM laboratory and by the RUU auto-analyzer. Stax (1987) compared the results and concluded that in:
   - Determinations of Na^+; K^+; Mg^{2+}: Results were in agreement;
   - Determinations of Cl^-; NO_3^-: The deviation was 3% between the measurements of both laboratories (to be ignored);
   - Determinations of SO_4^{2-}; Ca^{2+}: A systematic deviation of 25% existed between the measurements of both laboratories in the sense that for SO_4^{2-} the RUU results were lower and for Ca^{2+} the RUU results were higher than RIVM data;
   - Determinations of NH_4^+; PO_4^{3-}: RUU results were unreliable.

For the sake of consistency, RIVM results were used in the following, except when only RUU results were available. Where necessary, the deviations will be taken into account.

C. Groundwater recharge studies, based on its composition

Groundwater composition can be considered as part of a mass balance. Compounds brought in by precipitation can often be traced back to groundwater (Schoeller, 1962). Interfering factors are the effects of local pollution, including the attrapment of aerial deposition from nearby sources and, in general, the dry deposition, which is not caught by rain gauges. Another disturbing factor is the possible change in concentrations, resulting from various soil processes. A large component in the water balance is the evapotranspiration. The concentrations in groundwater can be compared with rainfall concentrations if the latter are multiplied by condensation factors, which are equal to the ratio: rainfall divided by recharge. This is to satisfy the mass balance. Usually, this type of consideration is based on chloride, because of its relatively conservative behaviour. The chloride ion is virtually unaffected by possible soil processes, leaving evapotranspiration as the only factor changing the concentrations. Hence, the recharge can be estimated from the groundwater composition if the rainfall composition is known. An elaboration of the Veluwe situation has been based on the chloride ion but takes into account the changes in the other groundwater components.

6.4.3.3. Hydrogeological structure of the Veluwe

The elevated situation of the Veluwe hills was caused by the formerly deposited sediments being pushed into the ridges (*Fig.6.91*) by large glaciers during the Saalian Glaciation. Pushing by ice occurred during

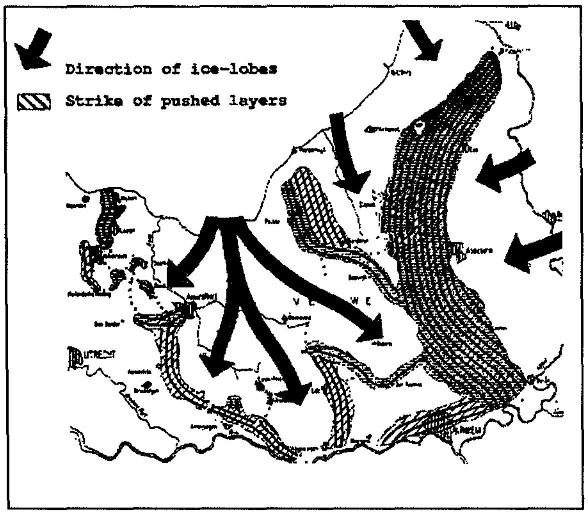


Fig.6.91. Schematic structure of the Veluwe area according to Maarleveld (1962).

various stages of the glaciation and also from different sides, leading to an intricate pattern of elongated ridges. The central ridge from Zwolle to Arnhem was formed by ice masses coming from the east, but in the northern part, an ice sheet was also present on the west side. An ice lobe in the present Gelderse Vallei formed the western ridges of the Veluwe hills. The southern hills were pushed from the south.

The removed sediments consisted of sandy material, deposited during earlier Pleistocene periods. Often, a clay layer was at the base of the pushing, implying that the subsurface of the ice-pushed ridges is sandy up to a clayey base. On the west side, the clayey base rests on coarse sand layers. These deeper layers consist of Middle Pleistocene layers with a relatively large permeability and resting upon finer sediments of a Lower Pleistocene and Tertiary Age, at a depth of roughly 200 m below surface. On the east side of the central ridge, the removed sand layers contained clay layers. The present transmissivity is reduced by the presence of sloping clay lenses.

In the east, the unpushed sediments of a Lower Pleistocene Age often consist of fine sand layers, down to roughly m.s.l.-100 m. At the southern flank of the Veluwe, Lower and Middle Pleistocene clay layers were at the base of the glacial pushing; they rest on coarse sediments of a thickness of some 20 m. A number of assymetric valleys incise the elevated ridges, especially at the east side. These valleys were largely formed under peri-glacial conditions, after the retreat of the ice masses, but partly they have been present from the beginning, resulting from the combined action of different ice-lobes. Deep incisions (with a depth of locally more than 100 m below m.s.l.) originated where the material was removed; these glacial valleys were later filled in, often with clayey material, but also with sandy deposits, eroded from the hills.

The Veluwe groundwater is fed by an amount of rainfall slightly more than the average rainfall in the Netherlands (*Fig.2.1*). The forest vegetation leads to a relatively large evapotranspiration. The composition of present rainwater is influenced by air pollution. Historical data are given by Leeflang (1938), Conrads and Buijsman (1973) and Van de Meent (1984). The actual, more systematic investigations of rainwater quality (RIVM,1989) indicate various regional trends. The chloride concentrations show a landinward decrease, indicating a concentration of about 4 $mg \cdot l^{-1}$ in the rainfall of the north-west and of 2.5 $mg \cdot l^{-1}$ in the rainfall in the south-east area. Other elements behave in a less pronounced manner. Schematized results are represented in *Table 6.15*.

6.4.3.4. The water balance

A. The water balance for the north-west Veluwe

Part of the Veluwe area was the subject of a regional and long-term water balance study in the context of water policy studies in the 1970s. The study (RID,1970) summarized the information available at that time with regard to the magnitude of the various components of the water budget. The area (*Fig.6.89*) for which the water balance was composed, had a surface area of 350 km^2. The period covered by the water balance was from 1952-04-01 to 1965-03-31 and, hence, the changes in storage of water in the balance area may be ignored. The upper boundary of the balance volume is the land surface and the lower boundary is assumed at a depth of 200 m, ignoring the flow in deeper layers. The horizontal boundaries either represent a flow line or a water divide, except for the subsurface at the north-west border, which forms the coast line of the Veluwe area with the former Lake IJssel. Hence, the inflow of groundwater may be neglected, but the outgoing flow will have a considerable magnitude. The balance has the form:

P(recipitation)=R(stream flow)+Q_{out}(groundwater flow)+E(evapotranspiration)

The various water balance terms were estimated as follows:

P. The determination of rainfall amounts was based on the observations during the period 1952-1968 which were used to compose isohyetes of average rainfall at the meteorological stations in the area. The pattern is represented in *Fig.6.92*, showing an orographic effect of the hills, causing a higher precipitation than the average rainfall in the Netherlands. A value was derived for the precipitation, P, in the balance area.

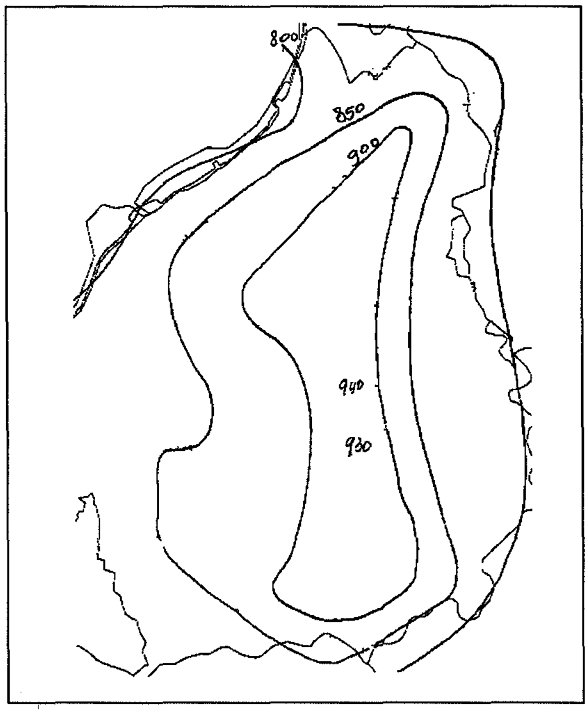


Fig.6.92. The average annual precipitation (mm·a^{-1}) in the period 1953-1968.

R. The determination of the stream discharge was based on discharge measurements of small streams flowing from the balance area in Lake IJssel taken by the Dienst der Zuiderzeewerken (ZZW). The total stream discharge, R, was derived from the measured values in the balance period. All streams originate within the balance area.

Q. An estimate of groundwater outflow. The amount of groundwater flowing out of the balance area was estimated by applying the equation:

$$Q_{out} = kH*i*L.$$

The transmissivity kH (m^2·day^{-1}) was estimated on the basis of two pumping tests, one in Harderwijk and the other at a well field near 't Harde, located on the south and north sides of the area, respectively. The tests yielded a transmissivity in the order of kH=8000 m^2·day^{-1}; the results, however, are not very accurate. For the calculations, a value of kH=6000 m^2·day^{-1} was used because indications are (Meinardi,1978) that at the boundary of the balance area, the subsurface to a depth of some 75 m is less permeable than on the test locations.
The gradient, i, in the direction of groundwater flow was taken from a map of isohypses (Meinardi, 1979), representing the average groundwater flow conditions in the balance area.
The width L of the outflow boundary was measured from a map, representing the balance area, which was determined on the basis of groundwater isohypses and flow lines.

In applying the above estimates, a determination of the average groundwater outflow, Q_{out}, becomes possible.

E. The amount of the evapotranspiration has to be estimated; direct measurement of the evapotranspiration in the balance area is not possible. The water balance equation is used to calculate the average actual evapotranspiration, this term being the only unknown. Elaboration yields the water balance of *Table 6.16*, resulting in:

$$E_a\text{=522 mm·a}^{-1} \text{ and } I=P-E_a\text{=315 mm·a}^{-1}$$

The accuracy of the evapotranspiration determined from the water balance equation is low, not because some relatively small terms were ignored, but mainly because the accuracy of the components represented in the water balance is low. Other ways to estimate the evapotranspiration were also elaborated as follows:

B. Estimates of the actual evapotranspiration using meteorological data
Based on values, E_0, for evapotranspiration (KNMI reports), where E_0 is the open water evaporation according to Penman (1948), the average open water evaporation for the balance area was computed: E_0=670 mm·a^{-1} (1952-1965).

Table 6.16. Water balance of an area of 350 km^2, in the north-west Veluwe in the period from 1952-04-01 to 1965-03- 31.

	10^6*m^3·a^{-1}	mm·a^{-1}		10^6*m^3·a^{-1}	mm·a^{-1}
Precipitation	293	837	Stream disch.	54	154
			Gr.w.outflow	56	161
			Evapotr.	183	522
TOTAL IN	293	837	TOTAL OUT	293	837

Table 6.17. Average values for precipitation and the open water evaporation, according to Penman (1948) holding for the Veluwe area in the period 1973-1986.

Year	P KNMIdistr.8 +50mm ($mm \cdot a^{-1}$)	E_o distr.8 ($mm \cdot a^{-1}$)	P-E_o KNMI- ($mm \cdot a^{-1}$)
1973	818	691	127
1974	977	669	308
1975	725	712	13
1976	585	776	-191
1977	866	643	223
1978	756	615	141
1979	934	612	322
1980	858	638	220
1981	979	599	380
1982	728	682	46
1983	993	656	337
1984	979	602	377
1985	853	610	243
1986	894	669	225
average	853	655	198

The potential evapotranspiration, E_p, for a specific vegetation can be estimated by applying the following vegetation factors (Makkink, 1960), with regard to E_o:

grass: f=0.8; heather: f=0.9; pine forest: f=1.0; deciduous forest: f=0.8; bare wasteland: f=0.4;

The land use of the balance area was estimated from standard topographical maps, showing the situation in the balance period. The vegetation consisted of:

- 28% grassland (E_p=540 $mm \cdot a^{-1}$);
- 17% heathlands (E_p=605 $mm \cdot a^{-1}$) and "bare" lands (E_p=270 $mm \cdot a^{-1}$);
- 55% forest area, estimatedly divided in 80% pine forest (E_p=670 $mm \cdot a^{-1}$), 10% deciduous forests (E_p=540 $mm \cdot a^{-1}$) and 10% open space (E_p=270 $mm \cdot a^{-1}$).

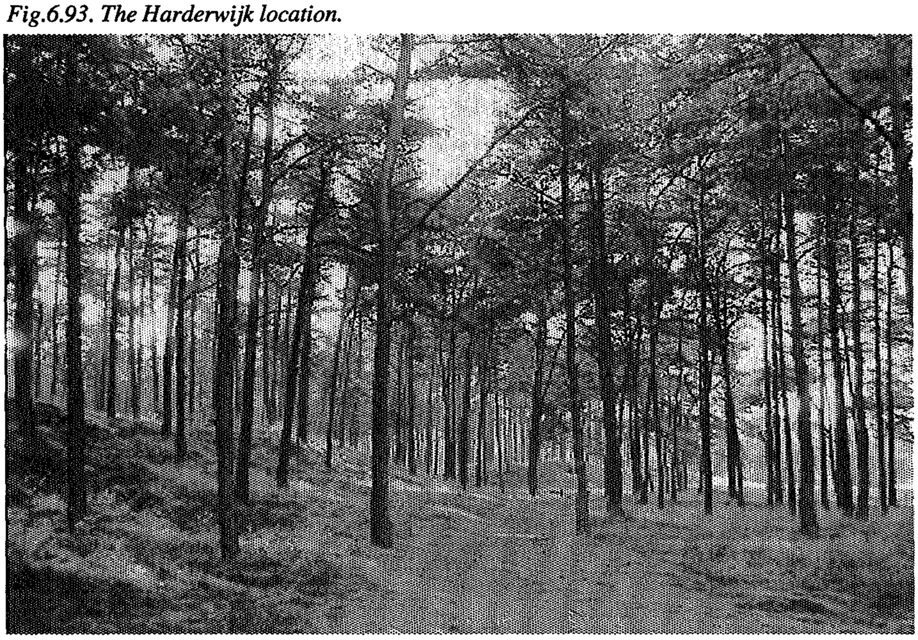
The weighted mean value of E_p in the balance area is E_p=577 $mm \cdot a^{-1}$ over the balance period. The calculated value of E_p is higher than the actual evapotranspiration E_a, computed with the water balance represented in *Table 6.16.*

The values of precipitation and open water evaporation for a more recent period, derived from KNMI data, are represented in *Table 6.17*; this is relevant for the later studies. In fact, both the average amounts of precipitation and the actual evapotranspiration do not strongly deviate from the values holding for the balance period given in *Table 6.16.* However, in estimating rainfall at other locations than the balance area, the spatial variation represented in *Fig.6.92* and *Fig.2.1* should be taken into account.

6.4.3.5. Results of local investigations

A. The location near LMG 364 at Harderwijk
LMG well 364 and a N well to a depth of 15 m were installed in a forest, east of Harderwijk (*Fig.6.93*). The local fieldwork (*Fig.6.94*) consisted of two VES,

Fig.6.93. The Harderwijk location.



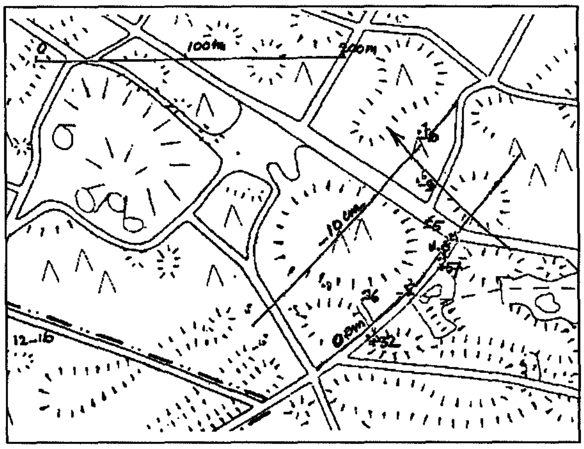


Fig.6.94. Situation showing isohypses.

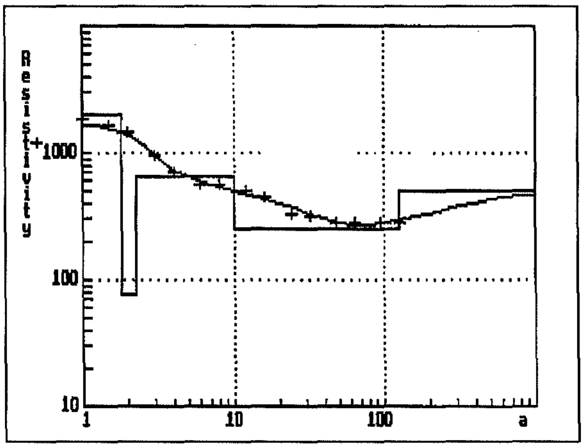


Fig.6.95. VES-1 Harderwijk.

an EM survey and the drilling of 16 boreholes, just tapping the saturated water. Water levels in the boreholes were measured and the wells surveyed. Samples had been taken from the screens of the N well and from each borehole. In *Tables 6.18* and 6.19, the results of the analyses are shown. Four samples from the N well were analyzed with regard to the tritium level (*Fig.6.96*). The fieldwork was done on 1986-10-01.

About 150 years ago, the area north-east of Harderwijk was occupied by heathlands and inland sand dunes (topographical map of 1850); this area was called the Beekhuizer Zand. In the second half of the 19th century, the dunes were fixed by the planting of pine trees, but a dune morphology can still be recognized at the site of the investigation.

In VES-1 (*Fig.6.95*), a thin loamy layer has been interpreted underneath the unsaturated zone. To a depth of about 10 m below surface, a coarse sand layer is present. The layer between 10 m and roughly 100 m below surface probably contains finer material because the resistivity indicates a formation factor of about F=3.9. The EM values gave no clear clue about the shallow soil, as the main factor determining the values turned out to be the depth of the varying water table. The isohypses in *Fig.6.94* indicate a flow to the north-west at a gradient of 1:1000 in agreement with the regional pattern. Interpretation of the tritium level (*Fig.6.96*) results in:

f=1.5 (factor indicating the deviation from Groningen rainfall); $I/p=0.53\ m{\cdot}a^{-1}$ (percolation); $I=185\ mm{\cdot}a^{-1}$ (p= 0.35);

The regional factor is larger than expected (f=1.05).

The chemical composition of the most shallow saturated groundwater and that of deeper water show significant differences, which will be related to differences in recharge (see *Table 6.17*); 1983 and 1984 were wet years. As a consequence, both series should be considered separately. Taking into account the rainwater composition of *Table 6.15*, the average condensation factors concerning compounds in samples from the shallow boreholes (*Table 6.18*) are:

$r(Cl^-)=13.5/4=3.4$; $r(SO_4^{2-})=36/7=5.1$; $r(Mg^{2+})=3.7/0.5=7.4$; $r(Na^+)=8.3/2.3=3.6$; $r(K^+)=2/0.23=8.7$;

Not all of these factors represent condensation, but some are in the same range. If the value of $r(Cl^-)$ is taken as a base, it follows for $P=900\ mm{\cdot}a^{-1}$ and $E_o=606\ mm{\cdot}a^{-1}$ (averages over 1984,1985; Harderwijk) that:

$I=P-E_a=270\ mm{\cdot}a^{-1}$; $E_a=630\ mm{\cdot}a^{-1}$; $E_a/E_o=1.04$ (wet years).

The same elaboration for the deeper groundwater results in:

$r(Cl^-)=4.4$; $r(SO_4^{2-})=6.4$; $r(Mg^{2+})=7.2$ $(Na^+)=4.3$; $r(K^+)=5.6$.

Fig.6.96. Tritium data for the N well.

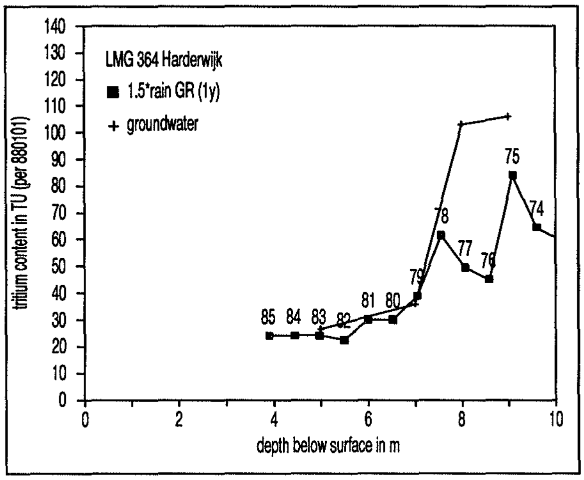


Table 6.18. Results from the shallow boreholes at Harderwijk. Observed concentrations in $mg \cdot l^{-1}$, except for pH and conductivity ($mS \cdot m^{-1}$)

No.	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
1	13	21	28		6	2	9	2		4.2	15
2	7	25	16		2	sp.	5	3		4.2	12.9
3	12	15	40		10	5	10	3		5.0	16.6
4	16	19	34		4	3	8	1		4.2	18.5
5	11	12	38		12	5	7	2		4.9	15.4
6	10	13	34		9	5	6	2		4.8	14.7
7	18	24	45		4	3	10	2		3.8	16.6
8	12	15	42		4	3	8	2		3.6	18.2
9	14	10	40		2	1	9	2		4.1	16.7
10	21	18	40		10	5	8	2		4.3	20.5
11	12	12	43		2	1	12	2		3.8	17.1
12	14	16	33		8	5	7	2		4.2	16.1
13	16	18	31		8	6	8	2		4.4	17.5
14	14	11	39		7	6	8	1		4.2	16.8
15	16	14	36		8	6	11	2		5.0	17.8
16	10	10	37		8	5	6	2		4.9	14.2
avg.	13.5	15.7	36	-	6.5	3.7	8.3	2.0	-	-	16.4

For P=840 $mm \cdot a^{-1}$; E_o=655 $mm \cdot a^{-1}$ (averages 1972-1986; Harderwijk):

$I = P - E_a = 190\ mm \cdot a^{-1}$; $E_a = 650\ mm \cdot a^{-1}$; $E_a/E_o = 0.99$ (average years).

B. The location near LMG 374 at Ermelo

More than 100 years ago (topographical map of 1850), the village of Ermelo was surrounded by vast heathlands. Much of the land has been planted by pine trees and the village has also grown. Only a small open terrain is left to the west of Ermelo (*Fig.6.97*). The heather vegetation has recently been changing into grassy components, presumably due to changes in rainfall quality. In that area, LMG well (M) and also a N well (to a depth of 15 m), were installed (*Fig.6.98*). Thirteen shallow boreholes, just reaching the saturated groundwater, were drilled. Two VES gave an indication on the structure of subsurface down to a depth of some 150 m. The measured EM-31 values did not show clear variations. The water levels in the boreholes were measured and the wells surveyed. Samples were taken from the screens of the 15 m well and from the hand-drilled boreholes. The analyses are shown in *Tables 6.20* and *6.21*. From the 15 m well, samples were taken to determine the tritium level. Only three samples were analyzed. The fieldwork was carried out on 1986-10-01.

The two VES indicate the unsaturated zone as the first layer present to a depth of 3.5 m (*Fig.6.99*). The

Table 6.19. Results from the N well at Harderwijk. Observed concentrations in $mg \cdot l^{-1}$, except for pH and conductivity ($mS \cdot m^{-1}$)

Depth	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
4m	16	18	41	sp	4	3	8	1	sp	4.2	18.5
5m	17	8	37	sp	6	4	8	1	sp	4.5	17.4
6m	19	6	48	sp	9	6	10	1	sp	5.0	19.0
7m	16	sp	39	sp	9	4	8	1	sp	5.2	15.4
8m	19	1	54	0.2	36	3	13	3	0.2	6.5	32.8
9m	19	sp	51	0.4	25	2	12	1	0.3	5.6	25.5
avg.	17.6	5.5	45	-	14.8	3.6	9.9	1.3	-	-	21.4

Fig.6.97. The Ermelo location.

Table 6.20. Results from the shallow boreholes at Ermelo. Observed concentrations in mg·l^{-1}, except for pH and conductivity (mS·m^{-1})

No.	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
1	6.1	49	20		1	sp	3	1		4.3	8.9
2	5.4	28	21		1	sp	3	1		4.4	8.3
3	7.7	16	19		1	sp	4	2		4.0	11.5
4	6.5	26	21		1	sp	3	1		3.6	13.1
5	5.7	5	21		1	sp	3	1		3.7	9.2
6	5.2	9	29		1	sp	3	1		4.2	11.5
7	6.1	10	31		1	sp	3	1		4.3	12.0
8	5.5	14	26		1	sp	3	1		4.3	11.4
9	6.1	10	22		1	sp	3	2		4.2	11.6
10	6.1	24	17		2	sp	3	1		4.0	12.4
11	7.3	11	21		3	sp	4	1		3.7	10.3
12	6.3	12	20		1	sp	4	1		4.3	10.2
13	6.0	12	19	-	1	sp	3	1	-	4.2	9.0
avg.	6.2	17.3	22	-	1.2	-	3.2	1.2	-	-	10.7

Table 6.21. Results from the N well at Ermelo. Observed concentrations in mg·l^{-1}, except for pH and conductivity (mS·m^{-1})

Depth	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
4m	8.5	8	26	sp	9	1.8	6.3	1.1	sp	5.3	12.7
5m	10.7	6	23	sp	16	1.4	7.5	0.9	sp	6.2	15.6
6m	8.8	7	22	sp	13	0.8	6.3	0.5	sp	5.8	13.1
7m	8.5	7	23	sp	14	0.9	6.3	0.6	sp	6.1	13.8
8m	8.4	7	23	sp	13	0.9	6.4	0.4	0.3	6.4	13.3
9m	10.3	6	21	sp	13	0.8	6.4	0.5	sp	7.0	13.0
avg.	9.2	6.8	23		13	1.1	6.5	0.7			13.6

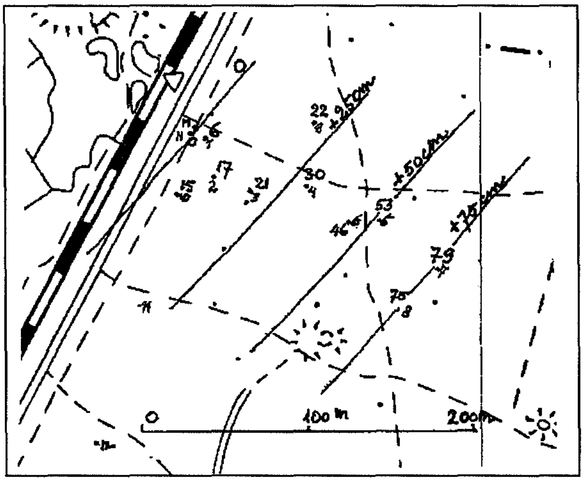


Fig.6.98. Situation showing isohypses.

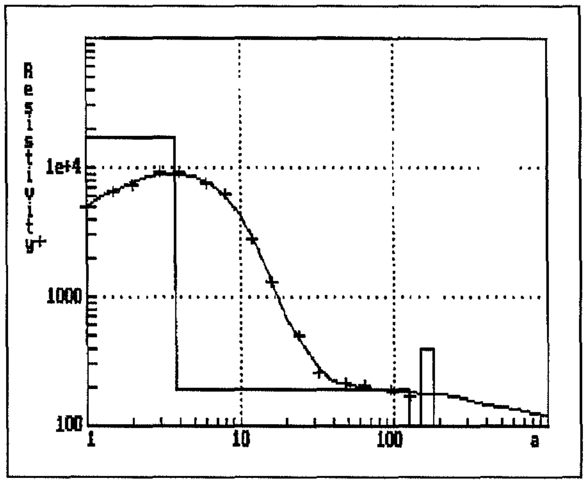


Fig.6.99. VES-1 Ermelo.

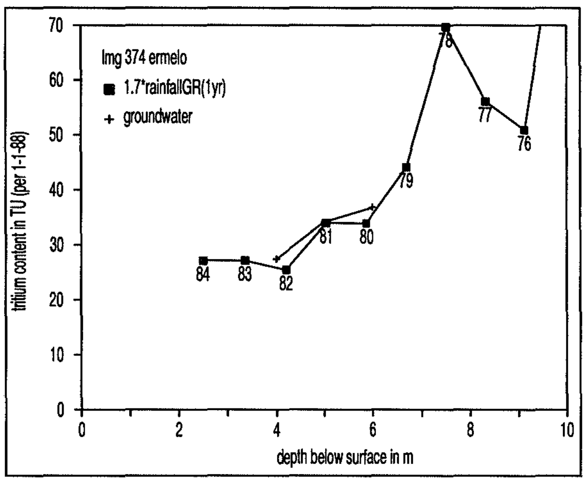
layer to a depth of approximately 120 m below surface probably contains finer material, since the resistivity indicates a formation factor of about F=3. The EM values gave no clear clue with regard to the structure of the shallow soil. The groundwater isohypses of *Fig.6.98* indicate a flow to the north-west at a gradient of 5:1000, which is in agreement with the regional trend. Tritium level leads to an interpretation (*Fig.6.100*):

f=1.7 (regional factor indicating the deviation);
I/p=0.86m·a^{-1} (percolation); I=300 mm·a^{-1} (p=0.35).

The regional factor is higher than expected. Apparently, the shallow saturated groundwater was recharged before 1984.

Again, the chemical composition of the shallow saturated groundwater and that of the deeper water show significant differences, which will be related to differences in recharge (*Table 6.17*). Both series concerning the groundwater composition should be con-

Fig.6.100. Tritium data for N well.



sidered separately. Taking into account the rainwater composition in *Table 6.15*, the average condensation factors concerning shallow groundwater are:

r(Cl^-)=6.2/4=1.55: r(SO_4^{2-})=22/7=3.1; r(Mg^{2+})=undet.;
r(Na^+)=3.2/2.2=1.5; r(K^+)=1.2/0.23=5.2.

Not all of these factors can be used. If a value of r=1.55 is taken as a base, it follows that for P=950 mm·a^{-1}; E_0=630 mm·a^{-1} (averages 1983 and 1984; Ermelo location):

I=P-E_a=610 mm·a^{-1}; E_a=340 mm·a^{-1}; E_a/E_o=0.54.

The same elaboration for the deeper groundwater results in:

r(Cl^-)=2.3; r(SO_4^{2-})=3.3; r(Mg^{2+})=2.2; r(Na^+)=2.8 r(K^+)=3.0.

For the deeper groundwater, most values are in agreement.
For P=820 mm·a^{-1}; E_0=655 mm·a^{-1} (averages for Ermelo over 1972-1986):

I=P-E_a=350 mm·a^{-1}; E_a=470 mm·a^{-1}; E_a/E_o=0.72.

C. The location near LMG 378 at Renkum

LMG well 380 is located east of the village of Bennekom in the valley of the Renkumse Molenbeek (*Fig.6.101*). Nearby, an N well is present. The 1985-10-16 investigation comprised the execution of four VES (*Fig.6.105*) and the covering of the surroundings by EM-31 measurements. The N well has been sampled twice, on 1985-10-16 and on 1987-03-23. The samples were analyzed with regard to chemical composition and tritium.

Between the villages of Renkum and Bennekom in the south part of the Veluwe, a long valley, running

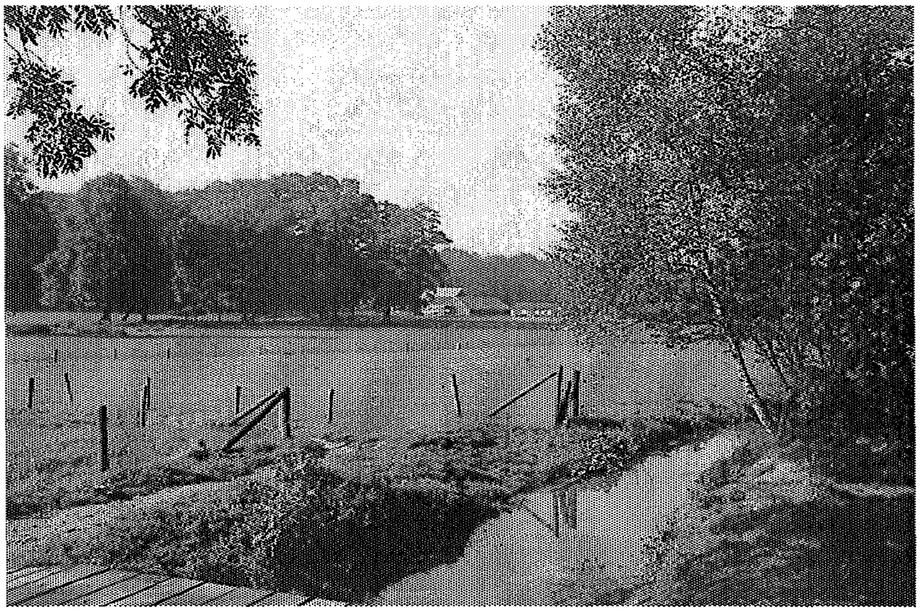
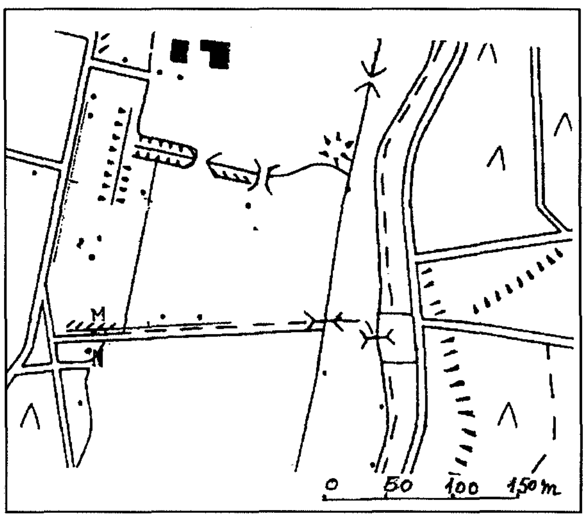


Fig.6.101. The Renkum location.

north-south, contains the Renkumse Molenbeek, originally a natural stream; it later was developed into a 'spreng'. In the upstream reach, the stream is recharged by a number of artificial springs. Further downstream, two parallel water courses run through the valley at different levels, enabling the former users to produce energy by the installation of water mills in between the courses. One of the paper-making factories developed into a large industrial site, which is still present at the confluence of the stream with the River Rhine. The southern part of the Veluwe is relatively densely populated. The stream valley contains a few meadows; the hills are covered by pine forests and arable land (*Fig.6.102*). At a distance of 100 m to the west of the investigation, a large maize parcel was present.

Fig.6.102. Situation in Renkum.



The four VES show much variation, which can be explained by the situation on the flank of a push-ridge, with differences in land elevation from 15 m (valley) to 25 m (hills) above m.s.l. The unsaturated zone in the valley (*Fig.6.103*) is thin and loamy; at the ridge (*Fig.6.104*), it has a thickness of 7 m and is sandy. The structure of the deeper layers is similar for all VES. The upper layers will contain fine sand to a depth of m.s.l.-5 m and coarse sand to a depth of m.s.l.-20 m. At the depth of m.s.l.-20 m, a clay layer resting on a deeper aquifer is interpreted in all VES. The EM values (*Fig.6.105*) show an interesting pattern. At the transition from hill to valley, a narrow zone with higher conductivities was observed, presumably representing sloping clay layers in the subsurface.

No isohypses were composed but the groundwater probably flows from west to east. The tritium data for 1985 show a good fit with the rainfall curve, the 1987 data to a lesser degree, leading to the interpretation (*Fig.6.106*):

f=1.1 (multiplication factor indicating the deviation from Groningen rainfall);
I/p=0.60 $m \cdot a^{-1}$ (percolation); I= 210 $mm \cdot a^{-1}$ (p=0.35).

The multiplication factor is equal to the regional value (f=1.10). The calculated recharge may not fully represent a forest situation due to the nearby presence of agriculture. The composition of the sampled water (only the 1985 results are given in *Table 6.22*) cannot be interpreted in the sense that it has a clear relationship with rainwater quality. Presumably, the nearby agricultural activities cause a deviation from rainfall concentrations, by the drifting of aerosols

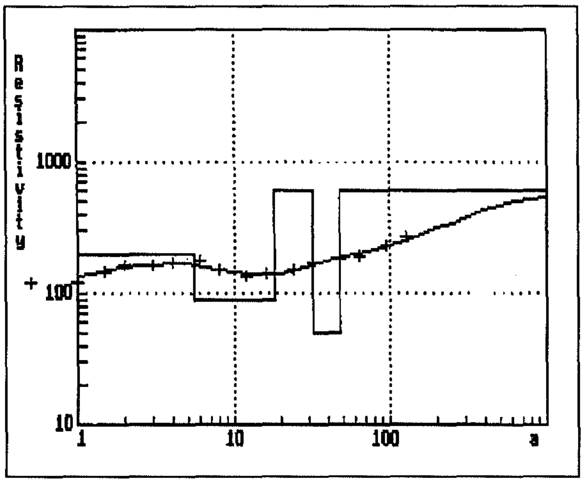


Fig. 6.103. VES-2 Renkum.

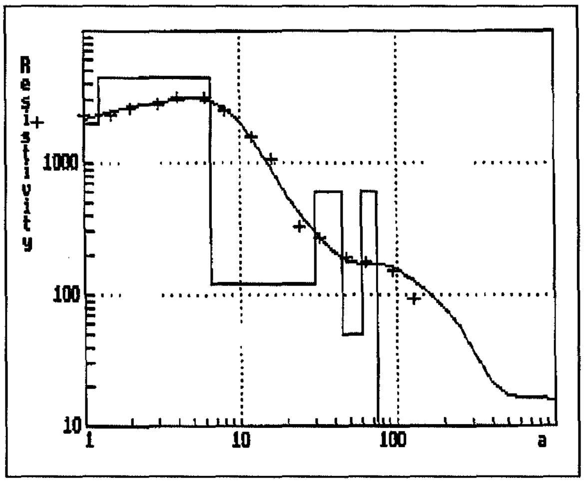


Fig.6.104. VES-4 Renkum.

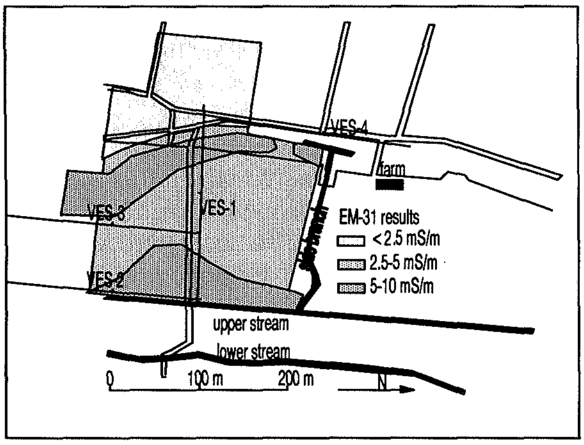


Fig. 6.105. EM-31 values (mS/m), Renkum site.

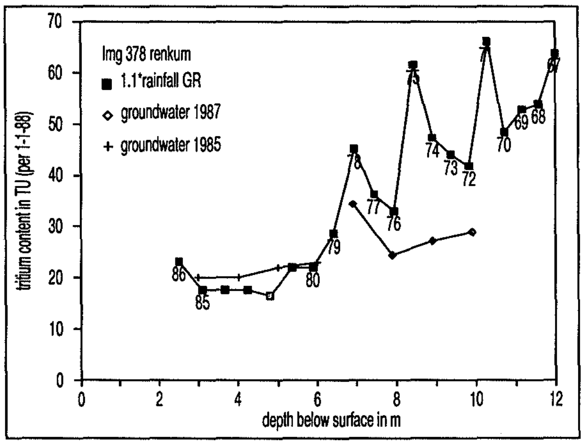


Fig. 6.106 Tritium data N-well, Renkum site

D. The location near LMG 380 at Laag Soeren

LMG well (M) and the N well at Laag Soeren are situated west of the village near the Soeren beek (*Fig.6.108*). The local investigation consisted of 14 shallow boreholes, reaching the saturated groundwater table, the execution of four VES and an EM-31 survey. The water levels in the boreholes were measured and the well rims surveyed. The boreholes and the screens in the N well were sampled and the water analyzed. Samples were also taken for a determination of tritium levels, but the analysis failed.

The Soeren beek flows on the north side of a broad asymmetrical valley. One kilometer downstream of the artificial springs, the stream has been diverted into an elevated bed to obtain the necessary difference in water levels for the running of a water mill (*Fig.6.107*, courtesy H.van Dam). The mill is out of operation at

Table 6.22. Results of the sampling on 19851016 of the N well at Renkum. Observed concentrations in $mg{\cdot}l^{-1}$, except for pH and conductivity ($mS{\cdot}m^{-1}$)

Depth	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
6m	18	16	49	sp				3.1	0.1	5.2	20
7m	24	19	65	sp				2.6	0.1	4.2	24
8m	25	13	73	sp				1.8	0.1	7.0	26
9m	23	12	55	sp				1.5	0.1	7.2	23
avg.	23	15	61	-	-	-	-	2.2	0.1	-	25.3

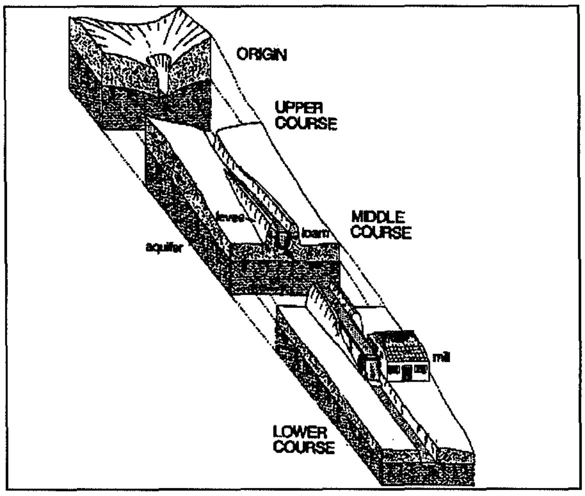


Fig. 6.107. Water mill scheme.

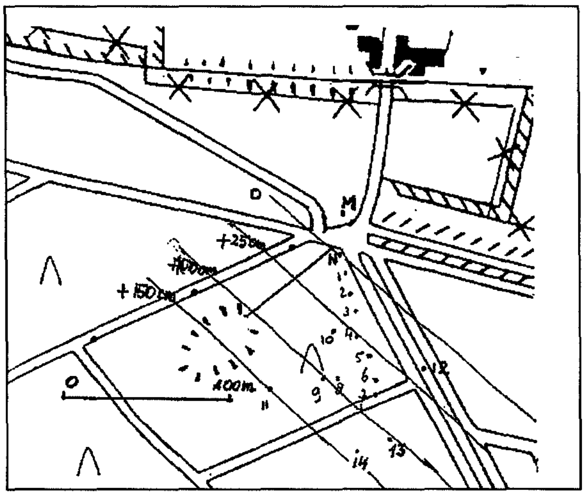


Fig. 6.108. Situation; isohypses, Laag Soeren.

present, but at the place of the former mill, a laundry is still using the stream water. The investigated site is near the laundry. The valley is covered by a pine forest where a few manors are constructed. Downstream of the laundry, meadows are present.

The four VES (*Fig.6.109*) indicate an unsaturated zone of a high resistivity. Below it, a thin loamy layer is found locally. The top of the aquifer, to a depth of 20 m to 40 m, consists of relatively fine sand. The aquifer contains coarse sand layers down to a depth of approximately 100 m, where it is rests on a loamy base. The pattern of the EM values (*Fig.6.110*) mainly shows the extension of a shallow loam layer. The highest values were found alongside the stream, indicating that the stream has a natural origin. The isohypses derived from the water-level measurements, indicate a flow in a north-easterly direction at a steep gradient of about 1:100. They correspond to the regional pattern.

The most shallow saturated groundwater and the deeper water show significant differences in relation to differences in recharge (*Table 6.23/24*). Both series were considered separately. Given the rainwater composition in *Table 6.15* and taking into account a chloride concentration of 2.6 $mg{\cdot}l^{-1}$, the average condensation factors concerning the boreholes are:

$r(Cl^-)=9.6/2.6=3.7$; $r(SO_4^{2-})=41/7=5.9$; $r(Mg^{2+})=1.6/0.3=5.3$; $r(Na^+)=5.4/1.5=3.6$; $r(K^+)=1.9/0.15=10.2$.

The factors for Cl^- and Na^+ are notably in the same range. If the value of $r(Cl^-)$ is taken as a base, it follows for $P=910\ mm{\cdot}a^{-1}$ and $E_0 = 606\ mm.a^{-1}$ (average 1984,1985; estimate Laag Soeren), that:

$I=P-E_a=250\ mm{\cdot}a^{-1}$; $E_a=660\ mm{\cdot}a^{-1}$; $E_a/E_o=1.09$.

The same elaboration for the deeper groundwater results in:

Fig. 6.109. VES-1 Laag Soeren

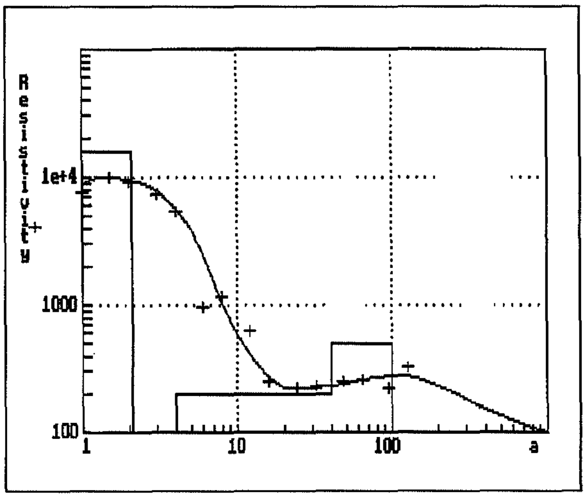


Fig. 6.110. EM-31 values (mS/m)

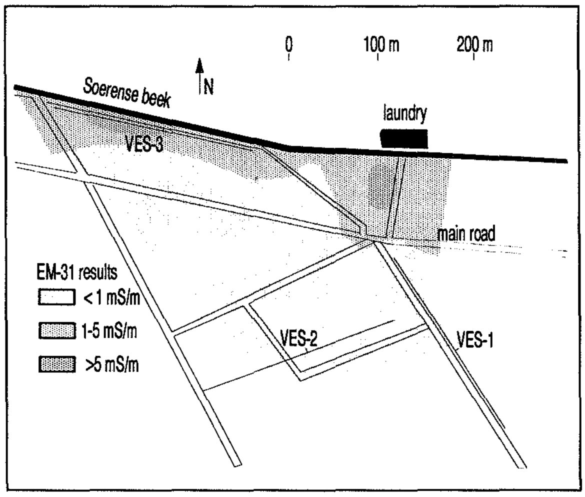


Table 6.23. Results from the boreholes at Laag Soeren. Concentrations in $mg{\cdot}l^{-1}$, except for pH and conductivity ($mS{\cdot}m^{-1}$)

No.	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
1	12	0.4	70		8	2	7	3		4.9	23.6
2	1	0.4	42		7	2	5	2		4.3	15.2
3	9	0.4	37		4	2	5	2		3.8	14.9
4	9	0.4	39		7	2	5	2		5.3	14.3
5	10	0.4	42		9	2	5	2		4.4	14.8
6	13	8.9	41		3	1	6	1		3.7	17.3
7	9	5.3	39		6	1	5	2		3.8	14.6
8	11	2.2	36		8	2	6	2		4.9	14.4
9	9	14	32		5	1	5	2		4.4	15.3
10	11	0.9	40		9	2	5	2		5.2	14.3
11	8	8.9	35		5	1	5	2		4.5	14.3
12	11	0.4	37		5	2	5	2		5.2	13.8
13	10	5.8	35		3	1	5	1		4.5	14.1
14	10	9.7	44	-	9	2	6	2	-	4.9	16.7
avg.	9.6	4.2	41		6.3	1.6	5.4	1.9			15.5

$r(Cl^-)=4.7$; $r(SO_4^{2-})=6.4$; $r(Mg^{2+})=5.3$; $r(Na^+)=4.7$ $r(K^+)=9.3$.

For $P=850$ $mm{\cdot}a^{-1}$ and E_0 = 655 $mm.a^{-1}$ (average 1972-1986; estimate Laag Soeren):

$I=P-E_a=190$ $mm{\cdot}a^{-1}$; $E_a=660$ $mm{\cdot}a^{-1}$; $E_a/E_o=1.01$.

E. The locations near the sources of the north-east sprengen

Some of the locations, studied during the fieldwork at the sprengen in June 1986, were visited again in December 1986. The Heerderspreng, the Horsthoeker Beek and the Tongerense Beek, in the North-east Veluwe, were revisited. The aim was to investigate the shallow groundwater, in order to study the most recent recharge of the sprengen concerned. To this end, a variable number of shallow boreholes were drilled down to the water table, just upstream of the sources. Samples were taken from the wells and analyzed at the RUU auto-analyzer. Moreover, the water of the sprengen was sampled again.

In former times the Heerderspreng (no. 1 in *Fig.6.90*) was used for industrial purposes and also for water supply, but at present the water does not serve any specific purpose. The spreng discharge has been reduced by a lowering of the groundwater table, resulting from groundwater withdrawals for a recreational project (Heerder Strand). During the June visit the discharge was already small, but in December virtually no discharge was observed. The sprengen are situated in a mixed forest area (*Fig.6.111*), although upstream an agricultural parcel is present. Two boreholes were used (HN and HZ in *Fig.6.112*).

Table 6.24. Results from the N well at Laag Soeren. Observed concentrations in $mg.l^{-1}$, except for pH and conductivity (mS.m-1)

depth	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
3m	12	0.1	43		12	1.4	8	1.2		4.7	15.2
4m	14	sp	57		12	1.9	9	1.3		4.3	18.6
5m	12	sp	53		12	2.0	6	1.5		4.5	16.9
6m	11	sp	50		14	1.9	7	1.6		4.7	16.3
7 m	11	sp	39		13	1.5	7	1.5		5.0	13.8
8m	11	sp	29		10	1.1	6	1.1		5.7	12.3
avg.	11.7		45.1		12.2	1.6	7.0	1.4			15.5

Fig.6.111. The Heerderspreng.

The Horsthoeker Beek (no. 3 in *Fig.6.90*) in Renderloo, was also installed for industrial purposes, but it no longer serves any economic purpose. The forest upstream of the sources is relatively young. In the past, the area was covered by heather. The sources (*Fig.6.113*) are situated in a forest area. The eastern boundary of the agricultural area of the IJssel Valley is found 100 m downstream. Seven boreholes were made (*Fig.6.114*).

The Tongerense Beek (no. 4 in *Fig.6.90*) originates in a broad valley, where seepage areas predominate. Only one of the sources, installed at the higher border of the valley and having a forested area upstream (*Fig.6.115*) was visited. Near the source, five boreholes were drilled (*Fig.6.116*).

The data with regard to the composition of the water samples taken from the boreholes can be elaborated in the same way as was done for the locations near the LMG wells. However, the effect of local pollution in a few wells was noted: The most prominent case is well R7 (*Table 6.25*). The analysis was carried out by the RUU auto-analyzer. In agreement

Table 6.25. Borehole results from the NE sprengen locations. RUU analyses. Observed concentrations in $mg \cdot l^{-1}$, except for pH and conductivity ($mS \cdot m^{-1}$)

Depth	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
HN	20	1	45		5	1.5	11	1.4		3.9	18.6
HZ	10	sp	21		10	0.8	6	0.7		5.0	9.3
R1	4	0.4	10		7	0.4	2	0.6		4.3	5.9
R2	23	1.9	47		10	1.3	12	1.0		4.2	18.7
R3	10	2.0	28		6	0.8	6	1.3		4.2	11.1
R4	15	5.6	29		6	3.0	8	1.3		4.3	13.6
R5	14	8.8	20		7	1.8	8	1.1		4.3	12.1
R6	15	10	26		6	1.1	26	0.7		4.2	14.3
R7	26	25	61		7	2.3	13	1.5		3.9	31.8
T1	19	2.9	34		5	1.4	9	0.8		4.0	16.5
T2	19	2.9	38		5	2.0	9	0.3		4.0	15.1
T3	16	25	37		6	1.6	8	0.9		3.9	24.9
T4	17	1.4	25		5	0.6	8	1.4		4.1	13.3
T5	14	17	34	-	9	1.5	8	2.5	-	4.1	16.5
avg.	15.8	7.5	32.2		6.7	1.4	9.5	1.1			15.8

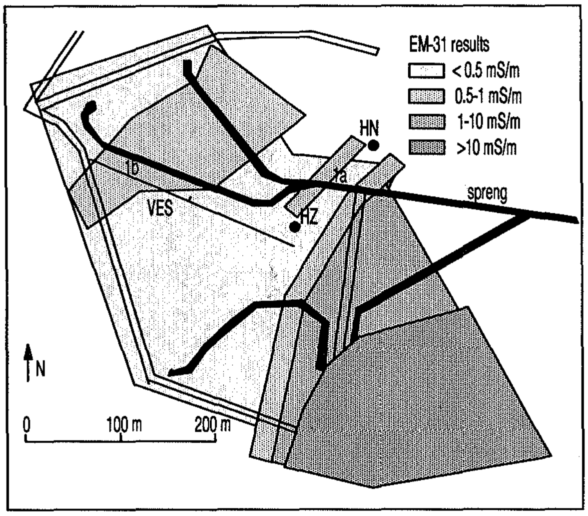


Fig. 6.112. Situation Heerde

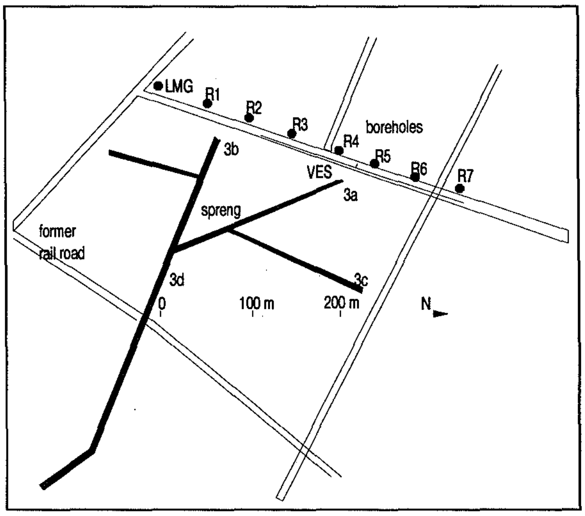


Fig. 6.114. Situation Renderlo

with the results of the ring test (section 6.4.3.2), the concentrations of SO_4^{2-} were increased by 25%.

The average condensation factors concerning relevant compounds in samples from the boreholes (HN; R-2 and R-7 excluded) are:

$r(Cl^-)13.9/3.75=3.7$; $r(SO_4^{2-})=34/7=4.9$; $r(Mg^{2+})=1.05/0.4=2.6$; $r(Na^+)=7.2/2.0=3.6$; $r(K^+)=1.05/0.2=5.3$.

Many of the factors are in the same range. If the value of $r(Cl^-)$ is taken as a base, it follows for $P=910$ $mm{\cdot}a^{-1}$ (average 1984,1985; estimate location NE sprengen), that:

$I= P-E_a=250$ $mm{\cdot}a^{-1}$; $E_a=665$ $mm{\cdot}a^{-1}$; $E_a/E_o=1.09$.

Fig. 6.113. Horsthoeker beek

6.4.3.6. The tritium levels of the various sprengen

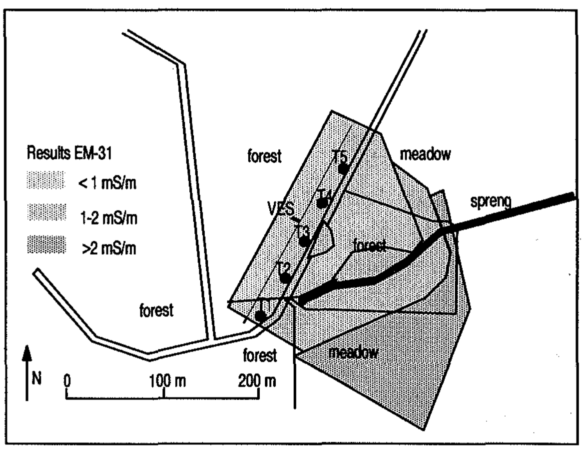
The interpretation of the VES in the north-east Veluwe leads to a clay layer at a depth of, on the average, D=50 m. The base of the deep aquifer underneath the south-east sprengen, at D=120 m, also follows from the VES carried out. The VES in the southern Veluwe indicate a sandy aquifer, having a base at D=35 m. In the south Veluwe a relatively thin upper aquifer is present, resting on a clayey layer and a deeper aquifer.

The averages of sprengen tritium data for the three distinguished regions (*Table 6.26*) were used to estimate the average groundwater recharge, by assuming that the mean values represent the mixed water of

Fig. 6.115. The Tongerense beek

variable ages (*Fig.6.88*), flowing to the drainage bases of three different regions. With regard to its tritium level, the groundwater recharge changed from water without tritium (before 1950), to water having an average level of 80 TU (reference date 1986-06), being the average of the levels in rainfall over the 30 years before 1984. It is assumed that water will remain in the unsaturated zone for two years (which is not always realistic); sampling was executed in 1986. According to the conclusions of section 5.7, account is taken of the enrichment of the tritium levels by the evaporation of intercepted rainwater, which results in groundwater values larger by a factor 1.5. Furthermore, the rainwater values in the years 1962-1965 (*Table 4.1*) were reduced by 50% to account for the observed difference between groundwater values and the extrapolated Vienna data.

Fig. 6.116. Situation Tongeren



The equation describing the tritium output (section 4.3.2.3) is:

$$\mathbf{c_{out}=c_{in}*(1-exp(-It/pD));}$$

where: c_{out} and c_{in} are average values in the sprengen and in the average recharging groundwater, respectively, in the past 30 years: t=30 years; D=aquifer thickness (m); p=0.35 (porosity); I=average recharge rate ($m \cdot a^{-1}$), to be determined. The results are represented in *Table 6.27*.

Individual tritium levels can be used to estimate the age distribution in the sampled water. The samples represent a part of the full recharge occupying a part of the aquifer (*Figs.6.117* and *118*). Measured tritium levels are caused by water younger than 30 years. That portion of the water can be calculated by dividing the tritium level in the sampled water by the average rainfall level (80 TU) over the period 1954-1984. Two cases can be distinguished:

a. The individual sample (*Table 6.26*) has a tritium level higher than the average value in the region (*Table 6.27*). In this case it is assumed that the water younger than 30 years, with an average level of 80 TU, is supplemented with just enough older water to attain the observed value (*Fig.6.117*).
b. The tritium level is less than the average value in the region. The older water, without tritium in this case, has to be supplemented with just enough water younger than 30 years to arrive at the measured level (*Fig.6.118*).

The equation z/D=(1-exp(-It/pD) gives the age distribution in the whole aquifer. Elaboration for the sam-

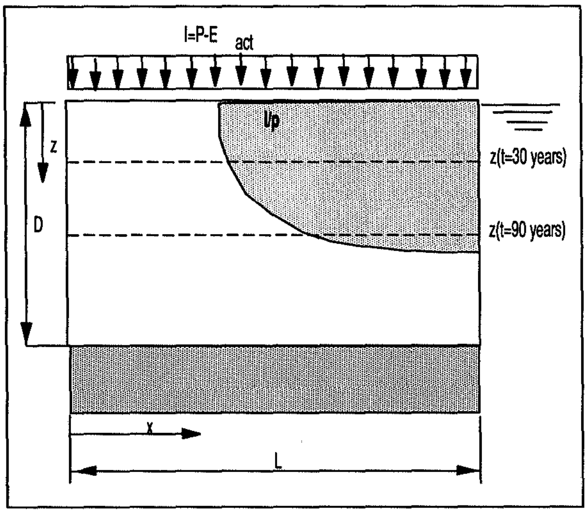


Fig. 6.117. Flow scheme for young spreng water

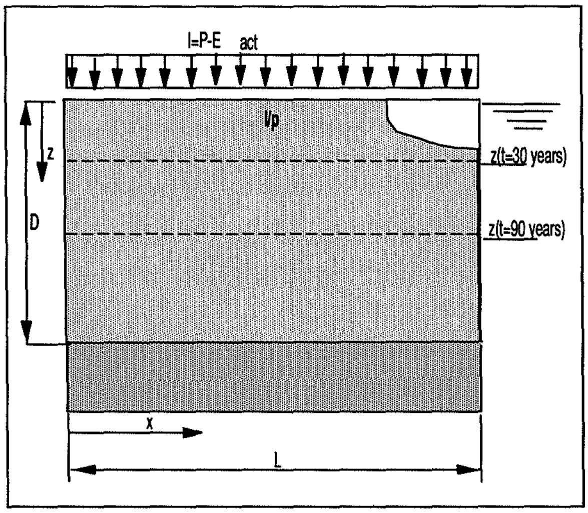


Fig. 6.118. Flow scheme for old spreng water

pled 'sprengen' water results in the estimate of the age distributions.

6.4.3.7. The discharge of water and solutes by the sprengen

A. Sprengen of the east Veluwe

The results of the measurements taken from the locations on the east flank of the Veluwe are given in *Table 6.28.* Except for the locations, 8a and 8b, the observations are found in the same range of values as shown by unpolluted groundwater. The pollution of the samples 8a and 8b may be explained by the situation of spreng no.8 in a holiday resort.

The quality of the sprengen water can be treated in the same way as the shallow groundwater. However, an extra difficulty is that the water of the sprengen is a mixture of groundwater, having different travel times in the subsurface. The age distribution of the sampled water can be approximated in the way previously indicated. It is useful to distinguish the observations from the north-east region and the south-east part of the Veluwe hills. The situation on the north side is different, because a confining clay layer was

Table 6.26. Tritium levels (TU) in the water of the Veluwe sprengen sampled in June 1986 (reference date)

South no.	TU	South-east no.	TU	North-east no.	TU
12	18	7a	19	1a	45
13a	29	7b	11	1b	18
13b	21	7c	36	2	22
14	29	8a	13	3a	47
15	20	8b	12	3d	33
16	39	9a	6	4a	29
17	20	9b	<5	4b	9
18a	63	9c	<5	5a	15
18b	58	10a	5	5b	21
19	26	10b	16	5c	25
20a	55	10c	8	6a	52
20b	22	11a	12		
20c	61	11b	28		
20d	35	11c	16		
21	64				
22	46				

Table 6.27. Groundwater recharge rates derived from measured tritium levels in sprengen (n= the number of samples)

NE Veluwe	(D=50 m, n=11);	$^3H_{avg.}$=28.7 TU;	I=0.259 $m \cdot a^{-1}$;
SE Veluwe	(D=120 m, n=14);	$^3H_{avg.}$=13.1 TU;	I=0.250 $m \cdot a^{-1}$;
S Veluwe	(D=35 m, n=16);	$^3H_{avg.}$=38.7 TU;	I=0.270 $m \cdot a^{-1}$;

observed at a depth of about 50 m, resulting from the VES interpretation.

The average ^{18}O level of the samples from the north-east sub-region (no. 1a to 6) is [^{18}O]=-7.28‰ (SMOW), which is more than the expected value of about -7.8‰ (SMOW). The deviation might well be caused by the effect of open water evaporation of rainfall, intercepted by the tree canopy. In the case of the evaporation of intercepted water, also the tritium levels will be affected. The average value of the ^{18}O level of the samples from the southeast flank (no. 7 to 10) is [^{18}O]=-7.57‰ (SMOW), which again is slightly larger than the expected value. The lesser deviation of the south-east samples can be explained by a smaller effect of evaporation from intercepted rain, the groundwater to a larger degree recharged within heathlands. The composition of the spreng water is used to estimate values of groundwater recharge. The land use of the recharge areas in the course of time was established with the help of topographical maps, representing the situation in different periods. The distribution of the ages of the water can be based on the tritium level for each sample.

Table 6.28. Observations at the sprengen of the east flank; all concentrations in $mg \cdot l^{-1}$. RUU analyses.

no.	Cl^-	NO_3^-	HCO_3^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	pH pH	cond. mS/m	disch. m^3/day	^{18}O ‰
1a	15	18.7	14	22	10	3.0	10	2.4	5.0	13.4		-7.0
1b	17	40.8	26	26	11	6	15	4	4.8	17.4	85	-7.0
2	12	5.3	13	9	8.8	0.7	5.1	1.0	5.0	12.2	40	-6.9
3a	11	2.4	11	23	6	1.3	2.7	0.8	4.1	9.7		-7.9
3b	19	3.3	22	10	-	-	4.3	1.0	5.0	11.3		-7.5
3c	22	3.7	10	12	9	-	3.5	1.2	5.1	-		-
3d	13	5.0	18	14	0	1.1	4.4	1.6	5.1	8.7	612	-6.8
4a	11	4.8	29	11	8	1.1	7	1.2	5.3	9.4		-7.7
4b	10	2.7	57	15	8	1.0	16	1.7	6.1	12.6	487	-7.4
5a	9	0.3	72	7	7	0.9	18	1.7	6.5	12.0		-6.8
5b	10	1.1	60	13	7	0.7	19	1.7	6.6	11.9		-7.4
5c	11	2.7	48	15	6	0.7	17	1.8	6.4	11.5	1408	-7.3
6	17	16.6	39	23	11	0.8	20	2.1	6.3	14.4		-7.6
7a	10	6.4	26	8	8	0.6	7.6	1.2	6.1	9.2		-7.3
7b	9	4.8	23	8	7	0.9	6.1	1.3	6.1	7.9		-7.5
7c	8	5.8	17	11	7	0.8	5.1	1.3	5.3	7.5	1104	-7.6
8a	41	12.4	24	20	19	1.8	13	3.6	5.1	17.0		-7.5
8b	37	12.0	24	22	18	1.9	13	3.6	5.6	17.3		-8.0
8c	-	-	-	-	-	-	-	-	6.2	16.8	956	-
9a	9	5	50	8	7	0.8	12	1.9	6.2	9.9		-7.3
9b	11	34	40	11	7	2.6	19	3.0	6.2	14.7		-7.1
9c	9	4	43	10	7	0.8	12	1.6	6.3	9.9	6044	-7.5
10a	7	2.1	58	8	5.8	0.6	18	1.6	6.7	10.8		-7.6
10b	7	3.9	28	13	5.4	0.6	11	1.4	6.3	9.9		-8.0
10c	8	3.8	31	11	5.9	0.6	12	1.3	6.3	10.8	2330	-7.3
11a	8	3.2	13	21	6.1	0.7	8.6	1.7	5.7	8.6		-7.4
11b	11	4.9	20	21	8.1	1.0	7.0	2.2	5.5	9.5		-7.9
11c	9	1.6		13	6.6	0.7	6.8	1.6	6.0	8.4	1431	-7.6

Table 6.29. Various contributions to sprengen on the east flank of the Veluwe and parts of total discharge, based on measured tritium levels

No.	<30yr Forest	<30yr Heather	30y-90yr Forest	30y-90yr Heather	>90yr Heather
1a	0.52	0.06	0.31	0.03	0.08
1b	0.21	0.02	0.28	0.03	0.46
2	0.23	0.06	0.08	0.30	0.34
3a	0.48	0.12	0.07	0.27	0.06
3d	0.34	0.08	0.08	0.31	0.19
4a	0.30	0.07	0.08	0.30	0.25
4b	0.12	0.00	0.18	0.27	0.43
5a	0.19	0.00	0.28	0.00	0.53
5b	0.27	0.00	0.34	0.00	0.39
5c	0.32	0.00	0.37	0.00	0.31
6	0.67	0.00	0.21	0.09	0.04
7a	0.17	0.07	0.19	0.13	0.43
7b	0.10	0.04	0.14	0.09	0.63
7c	0.32	0.14	0.23	0.15	0.16
9a	0.07	0.01	0.15	0.07	0.71
9b	0.03	0.00	0.16	0.07	0.74
9c	0.03	0.00	0.16	0.07	0.74
10a	0.05	0.01	0.17	0.12	0.64
10b	0.16	0.04	0.18	0.12	0.50
10c	0.08	0.02	0.17	0.11	0.62
11a	0.15	0.00	0.13	0.13	0.58
11b	0.36	0.00	0.19	0.19	0.26
11c	0.21	0.00	0.15	0.15	0.50

Five categories are selected (*Table 6.29*):

- water younger than 30 years, divided in forest and heathland recharge;
- water between 30 and 90 years old, again divided in water from forests and from heathlands;
- older water, where the vegetation of the recharge area consisted completely of heather.

Roughly 90 years ago, important changes in the vegetation occurred. That age also marked the start of industrialization and the use of fertilizer. With regard to the chloride levels in rainfall, it has been assumed that no changes occurred in time; however, a regional variation has been taken into account, such that in the north (Heerderspreng) the level is $[Cl^-]=3.75\ mg\cdot l^{-1}$ and in the south (Soeren beek), $[Cl^-]=2.6\ mg\cdot l^{-1}$ (RIVM, 1989). In between, intermediate values are assumed. Under these assumptions, differences will only be caused by differences in vegetation, also in the course of time and, as a consequence, different condensation factors.

The chloride concentration in each sample obeys the equation:

$$[Cl^-]_{sp}=[Cl^-]_{pr} * [(a_{30}+a_{30\text{-}90}+a_{90})*P/(P-E_h)+(b_{30}+b_{30\text{-}90})*P/(P-E_f)]$$

The average evapotranspiration E_h of heather and that of forest E_f are the unknowns. The amount of rainfall, P, is known. The chloride concentration $[Cl^-]_{sp}$ of the spreng water was measured; the composition of the local precipitation $[Cl^-]_{pr}$ can be estimated and the contributions from various sources denoted by a and b are given in *Table 6.29*. Ignoring the samples 8a and 8b, all samples have to obey the equation, resulting in a total of 25 equations, each with the same two unknown variables. The set of equations can be split up, depending on the subregions with varying features. The systems of equations were solved with the method of the least squares (multiple regression). Computed values of the multiple correlation coefficient, R, give an indication of how far the assumed models correspond to the measurements. Elaboration yields for P=850 (north-east=N-E) and P=900 $mm\cdot a^{-1}$ (southeast=S-E) the following results:

N-E :	$P/(P-E_h)=2.28$: $E_h=477\ mm\cdot a^{-1}$;	$P/(P-E_f)=4.36$: $E_f=655\ mm\cdot a^{-1}$;
S-E :	$P/(P-E_h)=2.96$: $E_h=596\ mm\cdot a^{-1}$;	$P/(P-E_f)=3.71$: $E_f=657\ mm\cdot a^{-1}$;
East:	$P/(P-E_h)=2.57$: $E_h=550\ mm\cdot a^{-1}$;	$P/(P-E_f)=4.19$: $E_f=685\ mm\cdot a^{-1}$;

The multiple correlation coefficients are R=0.43 (north-east sprengen); R=0.62 (southeast sprengen, except 8a and 8b) and R=0.80 (all eastern sprengen, except 8a and 8b). The value of R for the north-east sprengen is relatively low, indicating that other factors also play a role. Presumably, one of them is local pollution. For the total of all the eastern sprengen, a value of R=0.80 was computed, indicating that the applied model provides a satisfactory representation of the natural situation. The computed values for the evapotranspiration are in the expected range of values.

The relationship between other elements of the composition of spreng water and of rainfall were investigated by applying multiple regression, based on the same type of equation. The condensation factors to be used are assumed to be equal to the factors derived for the total of the eastern sprengen. This time, the unknowns are the concentrations in rainfall. Different equations were elaborated for the various compounds. The most simple equations had the form (for each of the considered compounds):

y=ax+b;

with: y is the measured concentration in the spreng samples;
x is a factor derived from the various condensation factors (*Table 6.29*);
a is a value indicating the concentration in precipitation (to be computed);
b represents an additional source of the compound involved (to be computed);

The results are:

For Na^+: $Na^+_{spr.} = 2.38(prec.)*x - 0.18$ ($mg \cdot l^{-1}$);
For K^+: $K^+_{spr.} = 0.16(prec.)*x + 0.34$ ($mg \cdot l^{-1}$);
For Ca^{2+}: $Ca^{2+}_{spr.} = 1.93(prec.)*x + 2.72$ ($mg \cdot l^{-1}$).

The computed concentrations in precipitation (a) correspond to the observed values represented in *Table 6.15*. For Na^+, virtually no additional supply (b) is involved but for K^+ and $Ca^{2=}$ extra sources have to be taken into account, which most probably represent an uptake of these elements from dissolution processes in the soil.

For SO_4^{2-} and Mg^{2+}, the chosen equations had the form:

v=ax+by+cz;

where x, y, z represent the contributions varying with time, derived from *Table 6.29*, and where a(<30y), b(30-90y) and c(>90y) represent the unknown rainwater concentrations in the past, which may take different values. These values represent the solution of the equation. In the case of SO_4^{2-}, all values in the spreng water were multiplied by a factor of 1.25 to take into account possible errors in the RUU analyses.

The results are interesting:

$Mg^{2+}_{spr.}$ =0.40*x(<30) + 0.50*y(30-90) + 0.58*z(>90) ($mg \cdot l^{-1}$);
$SO_4^{2+}{}_{spr.}$ =8.98*x(<30) + 2.72*y(30-90) + 4.55*z(>90) ($mg \cdot l^{-1}$).

The computed concentrations in recent precipitation correspond to the expected values. Apparently, an extra input of sulphate has occurred in the last 30 years, most probably resulting from air pollution. But also, the levels in the earliest period (presence of the Zuyder Zee, now Lake IJssel) are higher than in later years.

Another approach has been followed for the nitrate concentration, by assuming known input levels, according to Table 6.15, but an unknown denitrification in the subsurface. The equation becomes:

y=a*(px+qy+rv),

where the factor a has to be determined and all other variables have known values.

The result is:

$N_{spr.} = 0.39*N_{pr.}$

The conclusion is that: Denitrification can eliminate roughly 60% of the incoming nitrogen compounds, leaving the other 40% for percolation to the saturated groundwater.

B Sprengen of the south Veluwe

The results of the measurements taken from the sprengen in the southern hills of the Veluwe are represented in *Table 6.30*. The deviating chemical composition of many sprengen can be explained by the situation in the semi-urban area of Arnhem. The average value of the ^{18}O level (sample 20b excluded) of all samples from the southern hills is $[^{18}O]=-7.55‰$ (SMOW), which is slightly larger than the expected value. Also here, an effect of open water evaporation may cause higher values. The not polluted sprengen can be used to estimate the values of evapotranspiration. However, it is assumed that the evapotranspiration has the same values as determined for the eastern sprengen.

The appropriate condensation factors were used to estimate the possible contributon of rainfall quality to the spreng water composition in the same way as elaborated for the eastern Veluwe. The values derived by multiple regression, applied to the composition of the various samples from the sprengen at the southern hills, appeared to have hardly any relationship with rainwater composition. The most probable reason is that local pollution is important for the composition of the water from the sprengen. This type of pollution

Table 6.30. Observations at the sprengen at the south flank; concentrations in mg·l⁻¹. RUU analyses.

No.	Cl^-	NO_3^-	HCO_3^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	pH pH	cond. mS/m	disch. m^3/day	^{18}O ‰
12	17	0.1	184	23	10	1.1	49	6.0	7.0	23.2		-7.1
13a	12	2.6	27	25	9.5	0.7	13	2.3	6.3	8.4		-7.7
13b	12	3.5	43	19	8.8	0.7	16	2.2	6.5	9.2		-7.5
13c	11	0.8	65	18	7.7	0.8	25	2.7	7.2	14.2	3070	-
14	34	86	50	38	20	4.2	41	11	5.9	30.6		-7.5
15	23	19	38	24	14	1.5	18	3.1	6.1	16.0	334	-7.7
16	18	24	41	28	13	0.9	20	2.3	6.1	18.0		-7.8
17	31	39	35	16	20	3.1	16	3.3	5.4	19.2	2076	-7.4
18a	34	152	81	45	16	5.5	45	10.2	5.1	14.0		-7.8
18b	20	42	49	15	11	3.0	15	3.1	4.9	14.9		-7.4
19	21	9	32	13	12	1.6	13	4.2	5.1	17.7		-7.5
20a	20	30	25	36	12	7.3	7	1.9	4.5	15.2		-7.9
20b	5	0	90	8	3	2.4	18	1.0	6.2	11.5		-9.7
20c	12	16	27	45	8	1.5	6	1.0	4.1	13.9		-7.8
20d	15	5	-	37	-	2.4	-	-	7.3	24.0		-
21	17	19	17	26	12	2.8	12	2.0	5.6	13.7	788	-7.5
22	16	24	32	29	10	3.6	22	2.7	6.5	16.7	3300	-7.1

apparently cannot be represented by the equations used in the multiple regression, as could be expected.

6.4.3.8. Environmental implications

The various methods, used to estimate groundwater recharge, yielded comparable results, which will be discussed in combination with the other results for the central sand district. But it may already be concluded that the estimates, based on tritium data and on the effect of condensation, are in agreement. The chloride concentration was taken as a base for the computation of condensation factors, resulting in values for groundwater recharge and also for the actual evapotranspiration. Only a few values had to be disregarded, because an apparent contamination was present. The open type of rain gauge was used for sampling, in order to determine the various concentrations of compounds in precipitation. From the agreement between values of evapotranspiration, estimated by the condensation of chloride and calculated by other methods, it follows that no additional chloride will precipitate, e.g. as dry deposition, which is not recorded by the rain gauges. The first conclusion is:

1. **For Cl^-, the groundwater composition can be derived from rainfall by applying appropriate condensation factors.**

The determined condensation factors can be used to estimate the concentrations of the other compounds in recharge, based on the groundwater data. The results are repesented in *Table 6.31*. If no interfering effects are present the values should agree with those of *Table 6.15*, which are summarized in the top line. Other conclusions are:

2. **For NO_3^-, the approximation $N_{gr.w} = 0.4 * N_{pr.}$ yields satisfactory results, except for Harderwijk sh., Ermelo, Renkum and the southern sprengen, where probably an extra contamination occurs. The factor 0.4 represents the effects of various forms of denitrification.**
3. **For SO_4^{2-}, all the values in precipitation have to be increased by about 3 mgl⁻¹, probably being the effect of dry deposition. In the years preceding 1930, the Zuyder Zee caused slightly increased levels in Veluwe rainwater.**
4. **For Na^+, the groundwater quality can be derived from rainfall by applying appropriate condensation factors.**
5. **For K^+, the concentrations in groundwater are often roughly twice the expected values, probably because of the dissolution of K^+-ions in the soil.**
6. **For Ca^{2+}, the concentrations in shallow groundwater can be derived from rainfall, by applying a condensation factor. In the deeper soil layers, Ca^{2+}-ions go into solution.**
7. **For Mg^{2+}, the groundwater quality can be derived from rainfall by applying a condensation factor (again, a Zuyder Zee influence was noted).**

Table 6.31. Comparison of the actual rainwater composition and the calculated composition of the average precipitation in the Veluwe, as based on groundwater data divided by condensation factors; concentrations in mg·l⁻¹

	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}
Rain, Table 6.15	3-4	4.4	6-7	1.8-2.3	0.18-0.23	1.8	0.4
Harderwijk sh.	4.0	4.65	10.7	2.46	0.59	1.9	0.59
Harderwijk deep	4.0	1.25	10.2	2.25	0.29	3.4	0.29
Ermelo sh.	4.0	11.2	14.2	2.06	0.77	0.77	0.77
Ermelo deep	4.0	2.95	10.0	2.82	0.30	5.6	0.30
Renkum deep	5.2	3.36	13.7	-	0.49	-	0.49
Laag Soeren sh.	2.6	1.14	11.1	1.46	0.52	1.7	0.52
Laag Soeren deep	2.6	0	10.0	1.56	0.31	2.7	0.31
Heerde/Epe/Tong.	3.8	1.73	9.6	2.03	0.26	1.7	0.26
Sprengen east	var.	$0.4*N_{pr}$	9.0	2.32	0.27	2.3	0.27
Sprengen south	var.	$1.3*N_{pr}$	8.8	2.76	0.50	3.6	0.50

A reduction of the incoming flows of nitrogen compounds by a factor of 0.4 corresponds to the results of Boumans and Beltman (1991), who observed a reduction of between 20% and 50% at a general investigation of forest areas in the Netherlands. Another conclusion is that, apart from SO_4^{2-}, the effect of an extra aerial deposition, not recorded by the open type of rain gauges, is small for the major elements of the groundwater composition, at least in the Veluwe hills.

6.4.4. Tritium data of groundwater monitoring wells

6.4.4.1. Veluwe hills

The highest hills of the Veluwe are situated in a ridge between Hattem and Arnhem, with elevations of over 100 m above mean sea level (m.s.l.). But also the tops of the southern hills between Arnhem and Wageningen reach nearly the same height. A smaller ridge runs from Wageningen to Lunteren in the north and an even less elevated ridge is situated between Lunteren and the eastern central axis. In between the southern ridges, a plain is present, which is not underlaid by a former glacial basin, but which was filled in by fluvio-periglacial deposits, constituting a so-called sandr plain. More to the north, a hilly ridge is present between Kootwijk and Ermelo. This ridge borders the former glacial valley of the Gelderse Vallei in the south. Also, a glacial basin was found near Uddel which was filled-in up to a level that no low valley remained and that swamp conditions could not develop. The area is drained by the Hierder beek and by a considerable groundwater flow. Near the former coast with Lake IJssel, a dense network of small streams discharges the seepage water, which is fed by a regional groundwater flow. In general, the groundwater table in the Veluwe hills is at a depth that surface water courses are fully absent. Only near the fringes does the groundwater again approach land surface, but it is not so shallow that marshy conditions developed, like in the surrounding valleys.

The Veluwe subsurface consists mostly of sandy layers down to a great depth. For the interpretation of the tritium data from the LMG and PMG wells, D=100 m is taken. An additional problem is the residence time of the soil water in the unsaturated zone. As a working hypothesis, it is assumed (Appelo and Van Ree, 1983) that the vertical velocity in the unsaturated zone is in the order of $v_{unsat.}=3$ m·a⁻¹. Average values of groundwater recharge (*Table 6.32* and *6.33)* are:

LMG.forest:	n=6;	I/p=0.81 m·a⁻¹;	I=285 mm·a⁻¹;
LMG arable:	n=2;	I/p=1.20 m·a⁻¹;	I=420 mm·a⁻¹;
PMG.forest:	n=5;	I/p=0.79 m·a⁻¹;	I=275 mm·a⁻¹;
PMG.arable:	n=3;	I/p=0.77 m·a⁻¹;	I=271 mm·a⁻¹.

6.4.4.2. Gooi and Utrechtse Heuvelrug

The hills of the Utrechtse Heuvelrug and Gooi are not as high as the Veluwe hills. On the east side, the Gelderse Vallei is the remnant of a former glacial valley. On the west side no glacial valley is present, but deposits of the Rhine fluvial plain are. The west side of the hills has a gentle slope, except in the south, where the hills were eroded by the River Rhine. On the western fringes, a number of villages developed. For the interpretation of the tritium data from the LMG wells, D=100 m is assumed (*Table 6.34*). Average values are:

Table 6.32. Tritium observations at LMG wells in the Veluwe, (1-83= upper screen, 1983; 3-83= lower screen, 1983).

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m{\cdot}a^{-1}$	I_{avg} $mm{\cdot}a^{-1}$
364	harderwijk	forest	49	1	0.60	210
366	nunspeet	forest	44	78	0.88	309
372	ouwendorp	arable	38	38	1.38	484
374	ermelo	forest	16	11	0.84	292
375	ktw.broek	unknown	63	1	0.58	205
377	ede	arable	51	79	1.01	354
378	renkum	forest	20	10	0.82	288
379	oud reemst	forest	53	66	0.87	304
380	laagsoeren	forest	20	33	0.88	309
382	apeldoorn	built-up	50	85	1.08	379
384	arnhem	industry	39	59	1.03	362
387	arnhem	built-up	65	15	0.82	287

forest:	n=2;	I/p=0.92 $m{\cdot}a^{-1}$;	I=322 $mm{\cdot}a^{-1}$;
builtup:	n=2;	I/p=0.86 $m{\cdot}a^{-1}$;	I=302 $mm{\cdot}a^{-1}$;
grass:	n=1;	I/p=0.88 $m{\cdot}a^{-1}$;	I=307 $mm{\cdot}a^{-1}$.

6.4.4.1 IJssel Valley

The valley on the west bank of the River IJssel is almost literally overshadowed by the high Veluwe hills in the west. Much of the land belonged to farmers living in the villages on the east flank of the hills. They formerly used the wastelands for pasture and for hay fields. Only in the broad southern part did separate villages develop where the farming was similar to the kind of agriculture in the eastern sand district. In that area, a large swamp forest, the Beekhuizer Woud, remained undisturbed until 150 years ago. At that time, the forest was cleared and the land drained and reclaimed for agriculture. During the last century, the rest of the area was also largely reclaimed for modern dairy farming. However, some small forests still exist and the villages and the agricultural land are marked by groupes of large trees.

The subsurface of the valley consists of a large glacial basin down to a depth of more than 100 m below m.s.l. The deepest layers within the basin often consist of thick clay layers which fully confine the groundwater underneath. However, the upper layers are deposited by River Rhine branches and consist of

Table 6.33.. Tritium levels in PMG wells in the Veluwe (1990) and an interpretation.

PMG no.	Location	Land use	1-90 TU	2-90 TU	3-90 TU	$I/p_{avg.}$ $m{\cdot}a^{-1}$	$I_{avg.}$ $mm{\cdot}a^{-1}$
1029	heerde	heather	23	89	34	0.52	181
1030	epe	built-up	22	37	57	0.62	218
1039	harskamp	forest	22	46	43	0.69	243
1040	ede	built-up	15	35	99	0.85	298
1049	meulunteren	arable	17	50	41	0.71	249
1052	uddel	arable	28	38	35	0.60	211
1038	kootwijk	arable	und.	20	und.	1.01	353
1036	wezep	forest	und.	52	und.	0.42	148
1032	driesprong	forest	und.	16	und.	0.62	216
1033	dieren	forest	und.	29	und.	1.33	465
1035	koudhoorn	forest	und.	47	und.	0.86	303
1031	arnhem	forest	und.	9	10	0.79	276
1042	ermelo	built-up	23	15	35	0.28	100
1047	wekerom	grass	14	44	20	0.88	310

Table 6.34. Tritium levels in LMG wells on the Utrechtse Heuvelrug, Gooi (1-83= upper screen, 1983; 3-83= lower screen, 1983).

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
276	hilversum	forest	73	1	0.72	253
277	hilversum	unknown	56	81	1.15	402
278	laren	built-up	91	14	0.71	248
319	groenekan	grass	66	68	0.89	312
324	soesterveen	grass	65	31	0.86	303
325	amersfoort	unknown	41	1	1.14	399
326	bilthoven	built-up	55	82	1.02	356
327	doorn	forest	54	103	1.12	393

relatively coarse sand layers. For the interpretation of the tritium data from LMG and PMG wells, D=40 m is assumed. The interpretation (*Tables 6.35* and *6.36)* resulted in average values for the groundwater recharge:

avg.forest:	n=1	$I/p=0.75\ m \cdot a^{-1}$;	$I=263\ mm \cdot a^{-1}$;
avg.arable:	n=3;	$I/p=1.13\ m \cdot a^{-1}$;	$I=405\ mm \cdot a^{-1}$;
avg.grass:	n=3;	no realistic results.	

6.4.4.2. *Gelderse Vallei*

In former times, the stream valleys of the Gelderse Vallei were wet and swampy areas. Between the streams, slightly elevated lands offered more favourable circumstances for agriculture and a number of villages developed on this higher ground. The Gelderse Vallei as a whole is an assymetrical valley; the lowest zone is relatively close to the Utrechtse Heuvelrug. The streams flow from east to west until they reach a collector course following the lowest axis. Already in the Middle Ages, this central water course was improved in order to obtain better drainage of the wetlands. The canal, Valleikanaal, was dug in this century, again to improve the discharge of the inflowing stream water. In the recent past, the smaller streams have also been canalized and deepened. At present, an intensive animal husbandry is practised in the area, although still some nature reserves are present.

The shallow aquifer, down to the top of the confining Eemian clay layers, has a relatively small depth. The LMG wells did not yield interpretable results. For an interpretation of the PMG-wells, D=15 m is assumed (*Table 6.37*). Average results are:

arable:	n=1;	$I/p=0.93\ m \cdot a^{-1}$;	$I=325\ mm \cdot a^{-1}$;
grass:	n=2;	$I/p=0.75\ m \cdot a^{-1}$;	$I=263\ mm \cdot a^{-1}$.

The results are not very accurate because of the variation in the shallow depth of the base.

6.4.5. Discussion of results

The results obtained in the central sand district, consisting largely of hilly regions with deep groundwater tables and a natural vegetation, are different from the

Table 6.35. Tritium observations at LMG wells, IJssel Valley, (1-83= upper screen, 1983; 3-83=lower screen, 1983) and an interpretation

LMG no.	Location	Landuse	1-83 TU	3-83 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
381	busslo	unknown	45	1	1.00	352
382	apeldoorn	built-up	50	85	1.27	444
383	lieren	arable	55	30	1.05	369
385	terwolde	grass	44	1	1.78	624
386	hattem	grass	43	7	1.08	379

Table 6.36.. Tritium levels in PMG wells, IJssel Valley (1990) and an interpretation

PMG no.	Location	Land use	1-90 TU	2-90 TU	3-90 TU	$I/p_{avg.}$ $m{\cdot}a^{-1}$	$I_{avg.}$ $mm{\cdot}a^{-1}$
1037	loenen	arable	20	14	33	1.21	424
1024	gietelo	forest	25	37	und.	0.75	263
1025	hall	arable	13	20	und.	1.10	385
1027	oene	grass	29	5	und.	0.29	103

results in the other sand districts. Agricultural lands are mostly situated in the valleys, but the available tritium data is scarce in those areas and the interpretation is hampered by a locally varying hydrological situation. Yet, it may be concluded that the results are in agreement with the results for agricultural areas in the other sand districts.

However, the investigations in the central sand district provide a good opportunity to consider in more detail the groundwater recharge in areas with a natural vegetation. Various methods used to estimate the groundwater recharge in the Veluwe hills yielded comparable results (summarized in *Table 6.38*). The estimates, based on tritium data and on the effect of condensation, are in agreement. Hence, the value of porosity, p=0.35, assumed with regard to the tritium interpretation, is supported by the estimates based on condensation, derived from the groundwater composition.

The interpretation of tritium data from forest areas has to take into account problems of scale, implying that open spaces and areas planted with trees may behave differently in different cases. A relevant factor is that the sampled shallow groundwater was derived from rainfall in relatively wet years, limiting a possible reduction of the potential evapotranspiration due to soil water shortages. The calculated values for groundwater recharge in forest areas are in agreement. The values determined for the evapotranspiration of heathlands show less agreement, in all likelihood, because the character of areas, denominated by heathlands, will vary widely. Areas with an almost bare soil are present (and certainly were in the past), but so are areas covered with tall grasses.

The estimates of the overall groundwater recharge, derived from the average tritium levels of sprengen water, agrees with the other results in the sense that part of the recharge areas will not have a forest vegetation and, hence, the average evapotranspiration will be smaller. The same situation, with a larger part of open space in the recharge areas, also prevails with regard to the LMG and PMG wells, again causing a relatively small decrease in the estimated evapotranspiration. The elaboration of the long-term water balance resulted in less satisfactory results, presumably because the reliability of the values of the outgoing flows is low. Conclusions are:

1. The actual evapotranspiration of areas, with a dense tree vegetation at the Veluwe, roughly equals the Penman open water evaporation (E_0).
2. The effective porosity of the Veluwe subsurface is p=0.35.
3. The actual evapotranspiration of inhomogeneous forests, where forest lanes and open spaces are present, will be smaller than E_0. For Veluwe forest areas, the average actual evapotranspiration is approximately E_a=0.9*E_0.

Table 6.37. Tritium levels in PMG wells, Gelderse Vallei (1990) and an interpretation

PMG no.	Location	Land use	1-90 TU	2-90 TU	3-90 TU	$I/p_{avg.}$ $m{\cdot}a^{-1}$	$I_{avg.}$ $mm{\cdot}a^{-1}$
1051	nijkerk	built-up	17	22	und.	1.09	380
1044	barneveld	grass	33	13	und.	0.40	141
1047	wekerom	grass	14	44	und.	1.10	384
1050	driedorp	arable	13	44	und.	0.93	325

Table 6.38. Summary of results of different methods to determine the actual evapotranspiration in the Veluwe hills, all values in mm·a^{-1}; varying periods

	P	I	E_f	E_h	E_a	E_f/E_o	E_h/E_o	E_a/E_o
Location								
H'wijk sh.	900		630			1.04		
H'wijk dp.	840		655			1.00		
H'wijk ^3H	840	190				0.99		
Ermelo sh.	950			340			0.54	
Ermelo dp.	820			470			0.72	
Ermelo ^3H	820	300					0.79	
Renkum ^3H	850	210				0.98		
L.Soeren sh.	910		660			1.09		
L.Soeren dp.	850		660			1.01		
He/Epe/T sh.	910		665			1.09		
sprengen N-E	850		655	475		1.00	0.73	
sprengen S-E	900		660	595		1.00	0.91	
sprengen East	900		685	550		1.05	0.85	
sprengen avg.^3H	900	260			640			0.98
water balance	840	315			525			0.81
LMG forest	875	285			590			0.88
PMG-forest	875	275			600			0.90

P= Precipitation over the considered periods
I= Groundwater recharge, derived from tritium profiles and from the water balance
E_f= Actual evapotranspiration in forest areas, derived from considerations on chloride condensation
E_h= Actual evapotranspiration in heathlands, derived from considerations on chloride condensation
E_a= Actual evapotranspiration for areas with a mixed vegetation, derived from rainfall minus recharge
E_o= Open water evaporation according to Penman, derived from KNMI observations over the considered periods

6.5. The southern sand district

6.5.1.Geography and landscape

The southern sand district (*Fig.6.119*) covers the areas with a sandy soil in the provinces of North Brabant and Limburg. The loam (loess) soils of south Limburg are not included in the scope of this study. The regions from west to east are:

1. North-west Brabant
The sandy soils of north-west Brabant are found in the southern part of the province; the sand layers more to the north are covered with Holocene sea clay. The area represents the northern extension of the Brabant highlands; the shallow soil contains many relicts of relatively old geological formations. Buried fluviatile systems at shallow depths contain clayey zones.

2. Meierij van Den Bosch (Central Valley, north)
The central part of North Brabant is occupied by a valley, which is underlaid by a deep graben. Originally, the northern zone of the valley contained many wetlands in the form of 'broek' lands, covered by swampy forests. The draining streams converged near the town of Den Bosch, also implying wet soil conditions. The higher grounds, which were covered by heathlands and by some old agricultural land, are now reclaimed for agriculture. Poplar trees were planted in many 'broek' lands.

3. Kempen (Central Valley, south)
The southern part of the Central Valley is covered by sandy soils, drained by a few streams. The soils were relatively dry and poorly suited to agriculture. The land was scarcely inhabitated in former times and contained vast heathlands. At present, the wastelands are reclaimed, the farmers have turned to intensive animal husbandry. A relatively large part of the area is covered by pine forests. Many industries developed, leading to a relatively dense population.

4. Peel region
The soils in the Peel area are sandy, but subsurface flow and the natural drainage system did not have sufficient capacity to fully discharge all excess water, implying relatively wet conditions. Up to this century, the area consisted of uninhabited heathlands. The area was reclaimed for agriculture and it is now the site of a very intensive animal husbandry. The raised bog in the central part has become a nature reserve.

5. North Limburg
A large part of North Limburg consists of the valley

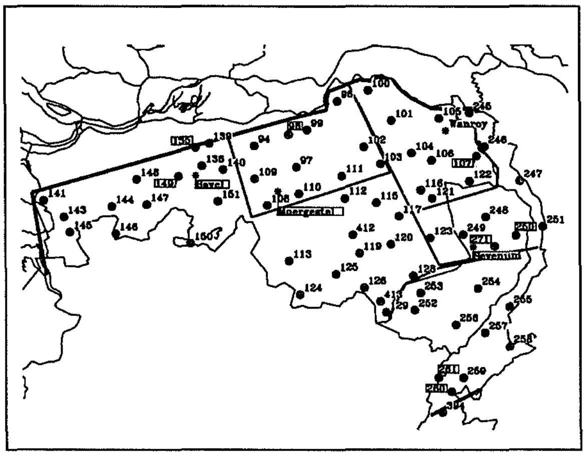


Fig.6.119. The location of the LMG wells and the investigated farms in the southern sand district.

of the river Meuse, covered by clayey soils. To the east, a sandy region is formed by old river terrasses. The land is used for a mixed type of agriculture, but nature reserves with mixed forests are also present.

6. Central Limburg
Part of Middle Limburg is the southern extension of the Peel region, with the same characteristicts as the northern Peel area. Most of the area is situated in the Central Valley; this area has relatively dry soils, reclaimed for agriculture. Intensive animal husbandry is practised. The old river terrasses, east of the river Meuse, are used for a mixed agriculture and parts are covered by forests.

6.5.2. Hydrogeological situation

The subsurface of the southern sand district consists of the flat fluvial plains of the rivers Rhine and Meuse, which, however, were thoroughly deformed by structural geological forces (*Fig.6.120*). The landscape and the soil are influenced by horst and graben features, running in a south-east to north-west direction. The district contains large zones, where the subsurface relative to the surroundings is rising. An example is found in the Peel area and the Central Valley west of it, which are still rising and subsiding, respectively. This was shown by recent earthquakes at the trending fault system. The rising Peel area had major consequences for the area west of it, because it halted the deposition of Rhine and Meuse sediments. In north-west Brabant, the shallow layers belong to the Tegelen and Kedichem Formations of a Lower Pleistocene age, containing clay and loam layers and often covered by a thin layer of cover sands. Consequently, the shallow sub-

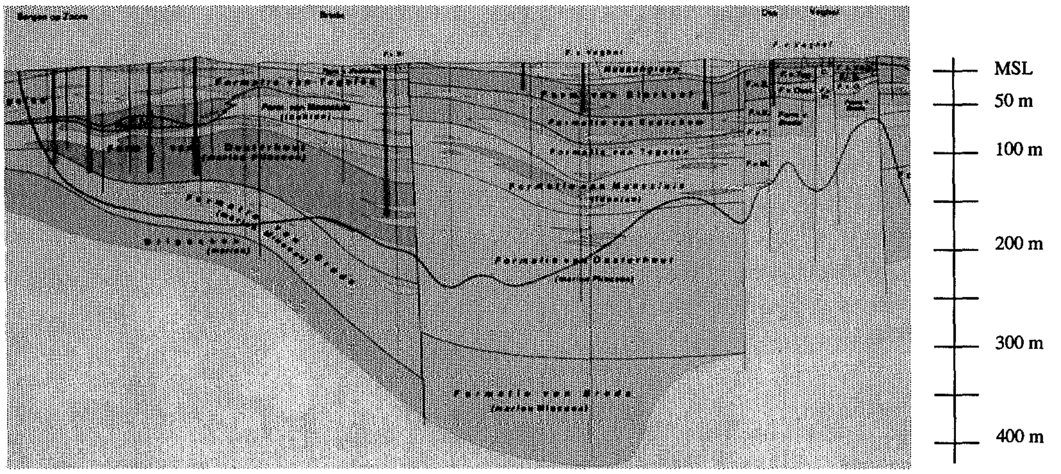


Fig.6.120. Hydrogeological cross-section of the southern sand district (Jelgersma, 1977).

surface cannot always transport the rainfall excess, implying surface runoff features and the existence of natural ponds, called 'vennen'.

In the subsiding Central Valley, sediments of local streams and eolian sediments were deposited in Middle and Upper Pleistocene Ages. These relatively thin layers, which geologically are combined in the Nuenen Group (RGD,1985), contain fine sandy, and organic and loamy material. The Nuenen Group is present over large areas of the northern Central Valley, where it hampers the recharge of the aquifer system below it, locally causing wet soil conditions. Fine sediments are largely absent in the shallow subsurface of the southern zone; the shallow subsurface often consists of relatively coarse sand layers, leading to relatively dry soils. The Peel region was lifted during a large part of the Pleistocene Age. The upper layers consist of relative coarse sand, belonging to the Veghel Formation of a Middle Pleistocene age, but covered with Upper Pleistocene and Holocene deposits. The transmissivity of the aquifer is relatively limited by its thickness of roughly 50 m, implying wet conditions in the winter period. East of the Peel region, the Venlo Graben represents a minor depression, which is filled in by Rhine and Meuse sediments, both containing sand and clay layers. The east bank of the River Meuse is also an uplifted area; older river terrasses are situated at levels above the present river level. The situation causes a deep groundwater table and at some places, the existence of perched groundwater bodies (an example is the Meinweg nature reserve).

A long-term regional water balance for the stream basin of the Dommel brook (*Fig.6.121*) was composed by RID (1967) and described by Visscher(1970) The balance consists of the following elements:

Precipitation	712 mm.a^{-1}	Stream flow	212 mm.a^{-1}
		Gr.water flow	5 mm.a^{-1}
		Evapotranspiration	495 mm.a^{-1}
IN	712 mm.a^{-1}	OUT	712 mm.a^{-1}

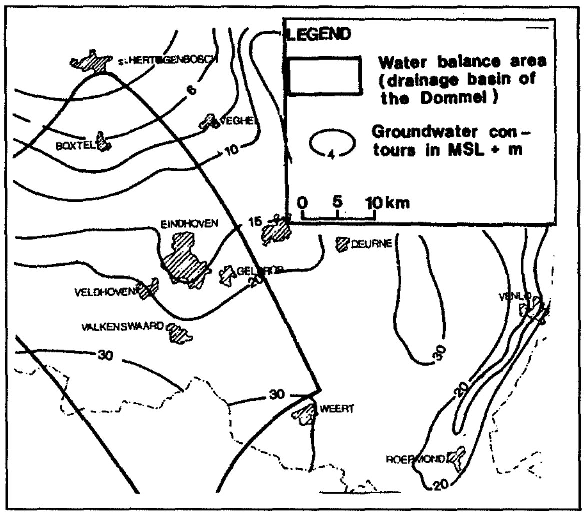
The actual evapotranspiration was calculated from the balance equation; it contains the inaccuracies of the other elements.

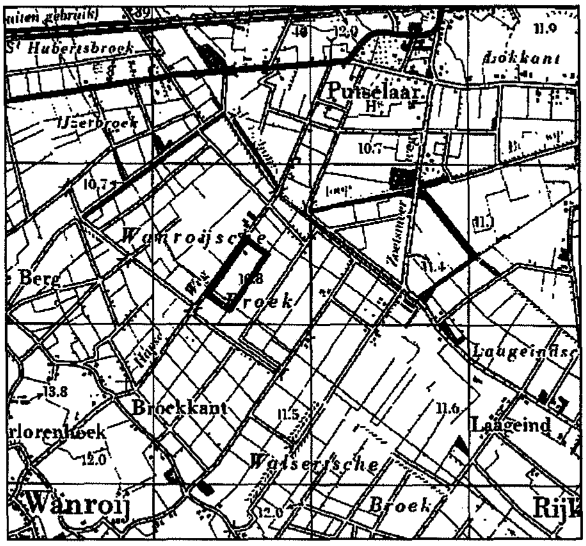
6.5.3. The Wanroij test farm

6.5.3.1. Situation and investigations

The village of Wanroij is situated on the flanks of the elevated Peel area, but the farmland was reclaimed in the former Wanroijse Broek (*Fig.6.122*), a flat and low zone to the east. In 1850, before the farmland had been

Fig.6.121. Drainage area of the Dommel brook.





·*Fig.6.122. Situation of the Wanroij test farm.*

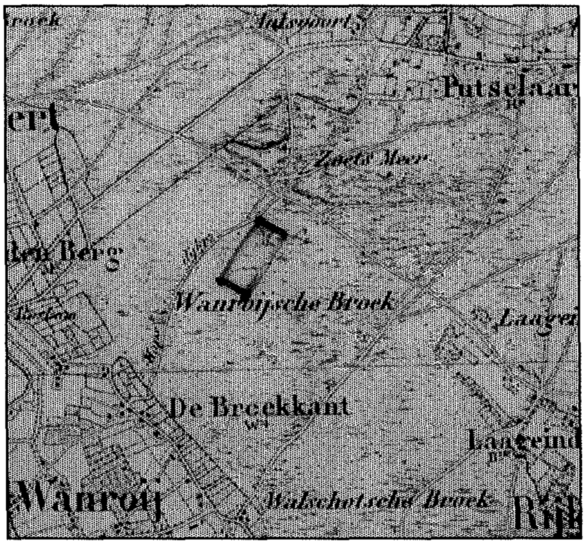
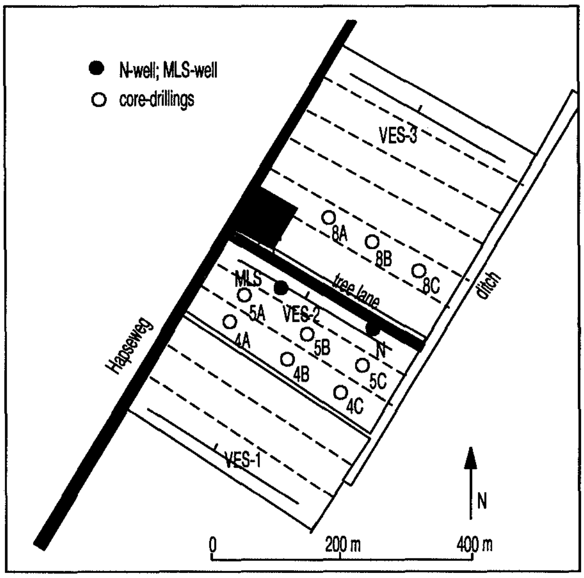


Fig.6.123. Topographical map of 1850.

reclaimed (*Fig.6.123*), passages in the swampy area between the Peel and the Land of Cuijk in the east were referred to as 'voort' (=ford). The broek area was most probably in a relatively recent past occupied by river gullies. Some remnants of these gullies can still be recognized in the 1850 Topographical Map in the form of the 'Zoets meer'. Reclamation included the digging of deep water courses in the SE-NW direction of the area. Because of the sandy soil, not many ditches appeared to be necessary.

A former gully system has long been present at the parcels 4 and 5 of the investigated farmland. Even now, the land surface is, relatively speaking, the lowest in that zone. In the same parcels, a thin clay cover, observed by the Stiboka pedological survey, may

Fig.6.124 The investigations on the farm.



have been deposited during incidental floodings of the abandoned river bed in geologically recent times. The presence of many iron concretions in the shallow soil of that area represents a nuisance to farming practices. The shallow subsurface consists of fluviatile sediments of the Upper-Pleistocene Age, belonging to either the Formation of Kreftenheye (Rhine), or to the Formation of Veghel (Meuse), or a combination of both. Deeper sandy layers belong to older Pleistocene formations. The sediments in general consist of coarse sand up to a depth of 50 m below surface, where the top of finer sediments of a Tertiary age has been observed. Thin loamy levels may be present within the sandy layers.

The investigations on the farm (*Fig.6.124*) consisted of a soil survey by STIBOKA based on 79 boreholes. The deeper soil was investigated by means of three VES, a coverage by EM-31 data, the execution of nine cored drillings to a depth of 8 m, in which observation screens were installed and the construction of a cable-tool drilling. Samples were taken, the water levels measured and the wells surveyed. A multilayer sampler was temporarily installed and used to take samples from the upper saturated zone.

After a recent project on land improvement, the land was parcelled in a regular grid. A limited number of large and deep ditches were dug and a system of tile drainage was installed. The land is laid in permanent pasture, in combination with the cultivation of maize for cattle fodder, sustaining a modern type of agriculture. Several rows of older poplar trees, in combination with recently planted tree lanes, give some variation to the landscape (*Fig.6.125*).

Fig.6.125. The farmlands at the Wanroijse broek.

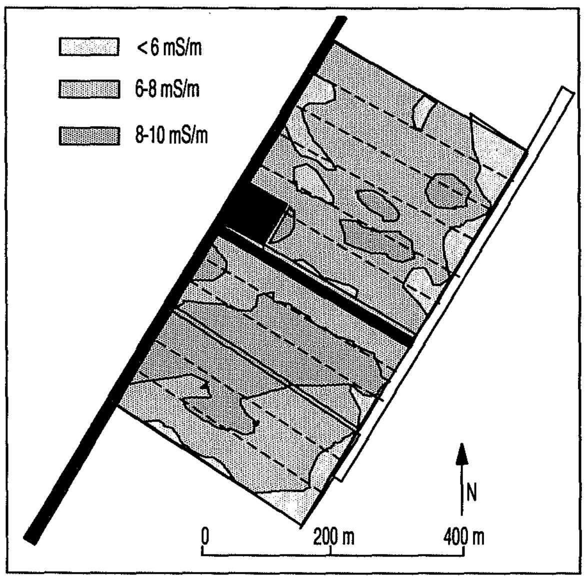
6.5.3.2. Geohydrological structure

The sedimentological analysis of the cored drillings lead to the interpretation that the shallow subsurface was, to a depth of some 8 m below surface, deposited within and near the main bed of a major river (probably the river Meuse reworking formerly deposited Rhine sediments). The main gully crossed the parcels 4 and 5. Within the main gully, secondary gullies were active. A number of fining upward sequences could be recognized, containing very coarse sand, but also finer material and even clay at one place. Incidentally, also a gully was present at other parts of the area, as indicated by the drillings at parcel 8. At parcel 8, the sediments were deposited under more quiet circumstances, implying sedimentation in a side-branch. Although the main sediments consist of coarse sand, the more quiet situation has lead to the development of some organic material.

The EM-31 investigation (*Fig.6.126*) confirmed the conclusions already derived from the sedimentological analysis and from the pedological survey. A zone of relatively high conductivity is present in the western parcels, which probably indicates the area with a buried river gully, at landsurface covered with a thin clay cover. Also the secondary gully at parcel 8 can be traced with EM-31 measurements.

The VES interpretation (*Fig.6.127* to *6.129*) showed a regular structure of subsurface. The measurements at the outer fringes indicate sandy layers in the unsaturated zone, whereas VES-2 in the middle of the parcel indicated more clayey layers. The interpretation corresponds to the pedological survey, also showing a clayey cover of the parcels 4 and 5. A remarkable feature is a transition at a depth of 13 m, where coarse upper layers with a resistivity of about 80 Ωm overly a layer with a resistivity of 150 Ωm. From the observed groundwater composition a formation factor (DGV-TNO,1981) for the upper layer can be derived of about F=5, This factor cannot be much higher for the underlying layer, implying that groundwater with a lower conductivity is present. The deeper groundwater probably will be older and less polluted.

Fig.6.126. Results of EM-31.



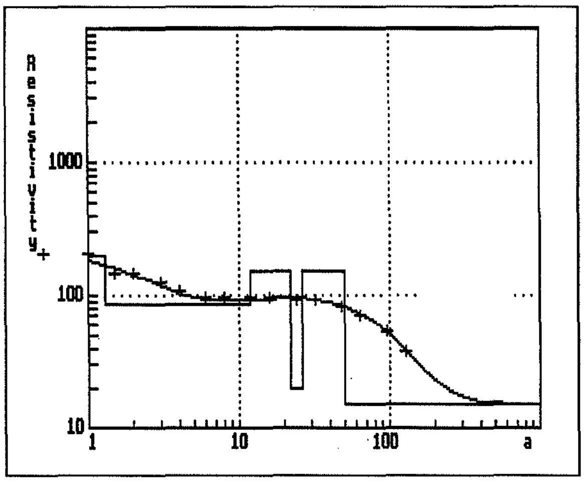


Fig.6.127. VES Wanroij-1.

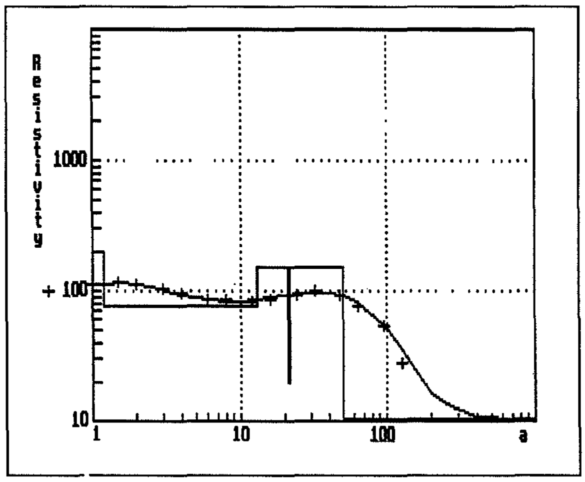


Fig.6.128. VES Wanroij-2.

It represents the regional flow coming from the Peel area. At a depth of slightly more than 20 m, a layer of relatively low resistivity was interpreted, representing the clayey top of the Tegelen Formation. Below that layer, again a sandy sub-aquifer is present, which has its base at a depth of 50 m, where clayey layers were observed. These clay layers most likely are the top of thick Tertiary formations and they will constitute the base of the aquifer system above it. The clay or loam layers at a depth of 20 m are relatively thin and, hence, they will not fully confine the underlying aquifer. On a regional scale, the full sandy layers, down to a depth of 50 m, will behave as one single aquifer. The hydrogeological soil structure has been sketched in *Fig.6.130.*

The groundwater heads observed on 1987-04-29 in the screens of the suction corer drillings yielded the pattern of isohypses represented in *Fig.6.131*. The direction of flow is from southwest to northeast, corresponding to the regional pattern.

The gradient in heads is more steep at the western part of the parcel than in the east. Presumably, the transmissivity at the west side of the parcel is lower, in relation to a different genesis of the soil. The ditch at the south-east side of the parcel is draining the groundwater.

The vertical groundwater percolation can be derived from the measured tritium levels in the N well (*Fig.6.132*). The downward groundwater velocity at the groundwater table is: $I/p=0.89\ m{\cdot}a^{-1}$ and the groundwater recharge is $I=310\ mm{\cdot}a^{-1}$, at $p=0.35$. The recharge may be higher than the local rainfall excess, because intensive sprinkling is applied by the farmer. At the lower reaches of the tritium profile, deviations from the expected values occur, maybe to be explained by the contribution of older groundwater. The multiplication factor $f=1.05$ is lower than the determined regional value in rain water, which is $f=1.15$.

Fig.6.129. VES Wanroij-3.

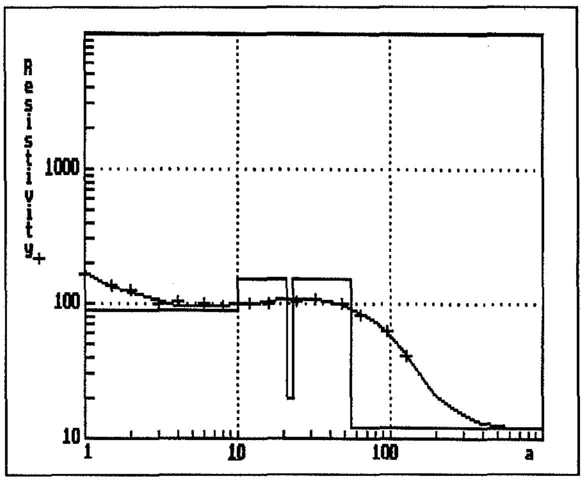
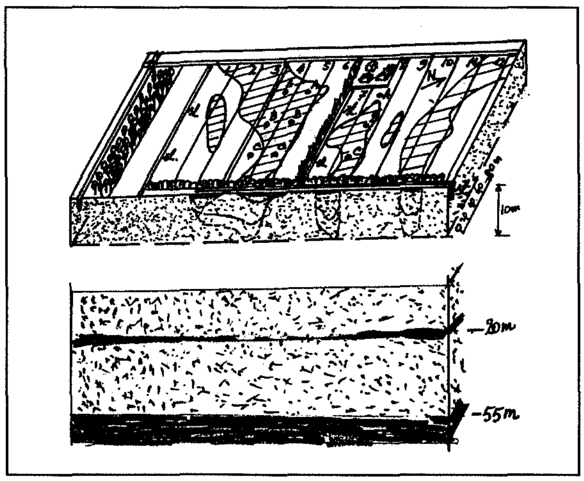


Fig.6.130. Soil structure.



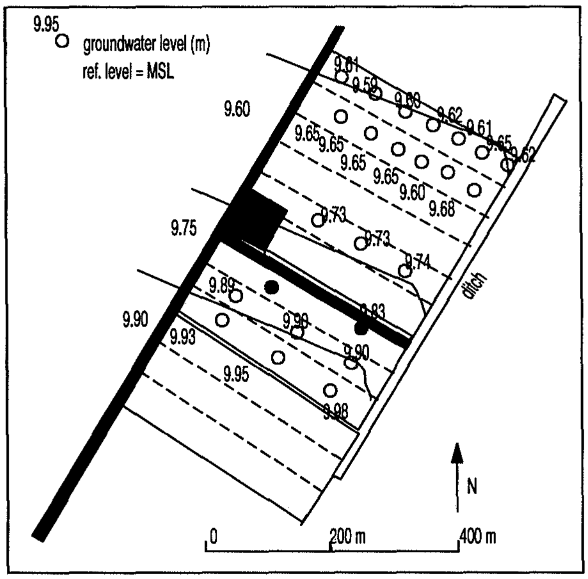


Fig.6.131. Isohypses on 87-04-07.

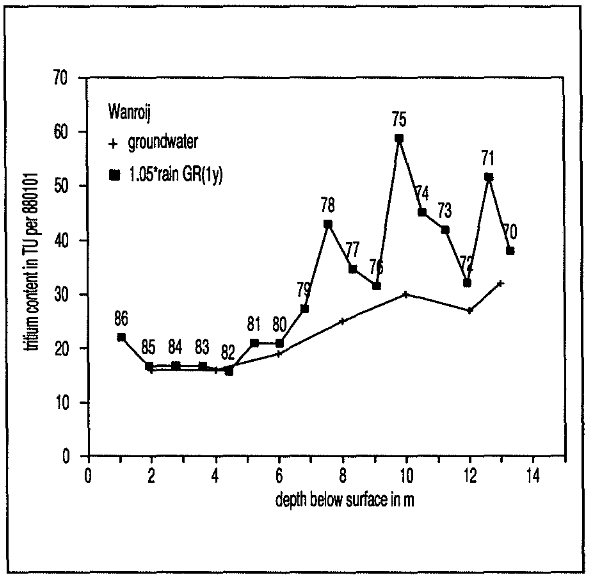


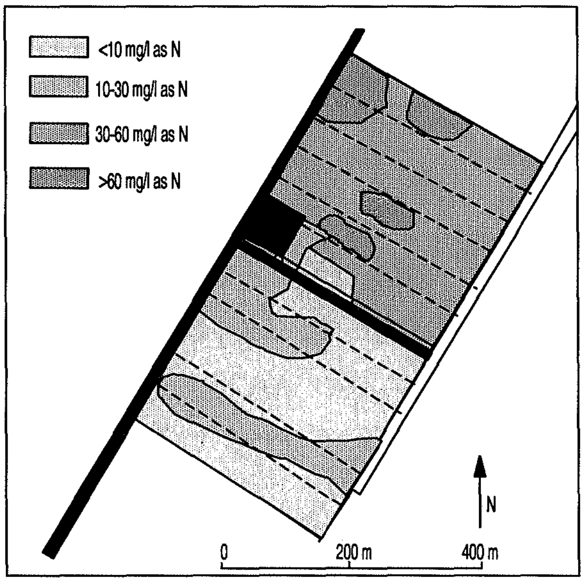
Fig.6.132. ^3H levels in the N well.

6.5.3.3. Environmental implications

The situation of the farm and the structure of the shallow subsurface, largely determined by the presence of a buried river gully, have specific consequences with regard to the quality of the groundwater.

a. The hydrological situation has changed. The former swamp has been turned into a well dewatered region. An area, where seepage dominated in the old situation, changed into an area of groundwater recharge. The tritium profile indicates that, at least to a depth of 13 m, a downward groundwater flow is prevailing; maybe at deeper layers still a regional flow of groundwater enters the area, locally discharged at the deep water courses.
b. The situation in former times, where the parcels 3, 4 and 5 formed a relatively low area, receiving seepage water from the subsurface of the Peel area, implied that dissolved substances were imported. Most of them continued to flow with the groundwater discharge to the larger surface water, but notably iron compounds precipitated, presumably in the form of iron sulfide. After reclamation, local rain water penetrated into the soil, leading to a remobilization of the iron and a subsequent precipitation in the form of iron concretions.
c. The filling-in of the remaining river bed with clayey and also organic material resulted in soil conditions promoting denitrification. Even at the present high nitrogen loads, the outflow of nitrates from the shallow soil remains small at the western half of the parcel. At the east part of the farmland high nitrate concentrations were observed (*Fig.6.133*). Observations with the multilayer sampler (*Fig.6.134*) confirm the findings of the observation screens. At the upper 20 cm of the saturated groundwater, a nitrate reduction occurs and a simultaneous increase in sulphate levels. Below that level not many changes occur anymore.
d. In deeper layers a further denitrification (*Fig.6.135*) was remarked, leading to a reduction with roughly 50%, if compared to the nitrate concentrations entering the groundwater in the saturated zone.

Fig.6.133. N concentrations shallow groundwater ($mg \cdot l^{-1}$ as N).



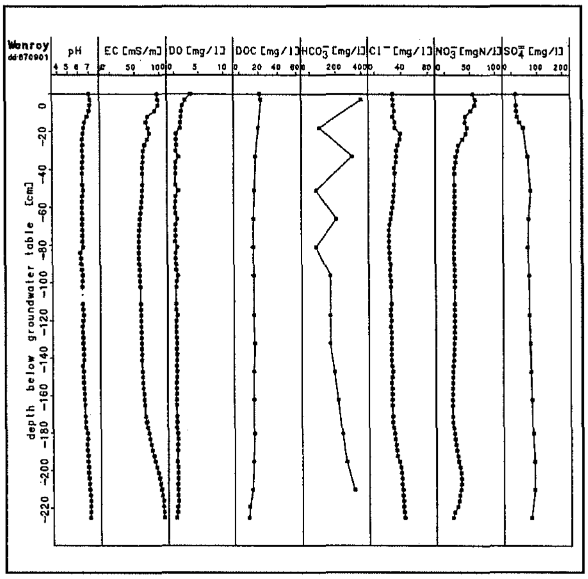


Fig. 6.134. Results multi-layer sampler, Wanroy farm

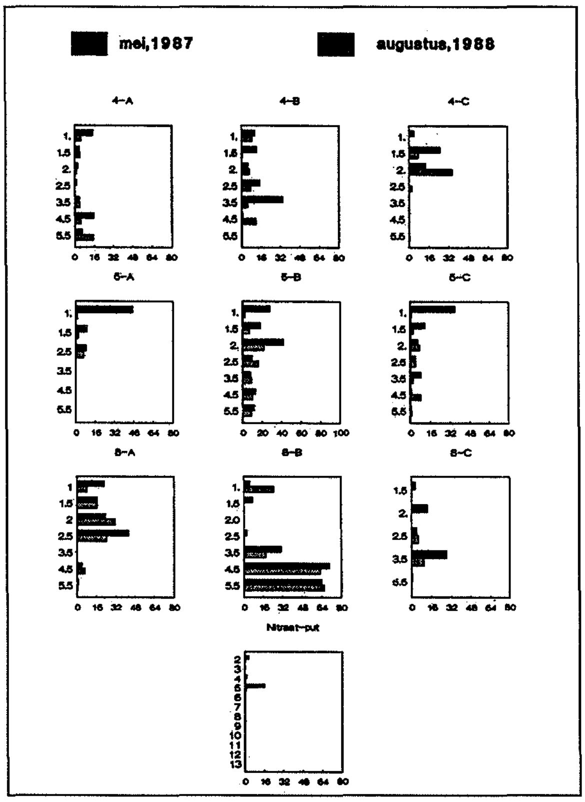


Fig.6.135. N concentrations deeper groundwater; Wanroy

6.5.4. The Moergestel test farm

6.5.4.1. Situation and investigations

The parcels of the Moergestel test farm (*Fig.6.136*) are situated west of the village, but dispersed over a wide area. The farmyard forms part of the neighbourhood Heikant; one parcel is found just east of the farm, then follow a small pine forest and the next parcel. The parcel in the Beerze brook valley is at a distance of some 2 km from the farmyard. The Heikant neighbourhood already existed in the year 1850 (*Fig.6.137*) and some arable land was reclaimed, like the land of the present parcel near the farmyard. This land was fertilized by manure from the farm cattle, which was grazing on the vaste wastelands further to the east. The upper layers consist of a few decimeters of black humus sand.

Fig.6.136. Situation of the Moergestel test farm.

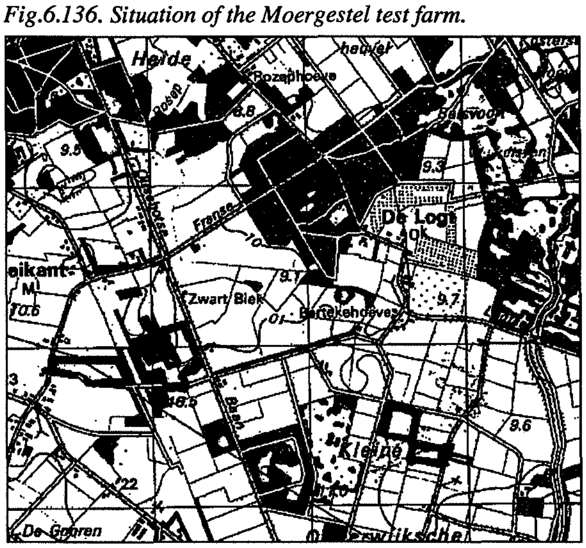
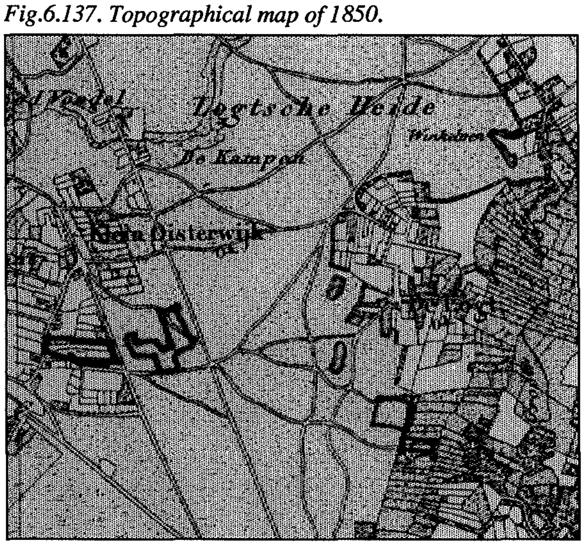


Fig.6.137. Topographical map of 1850.



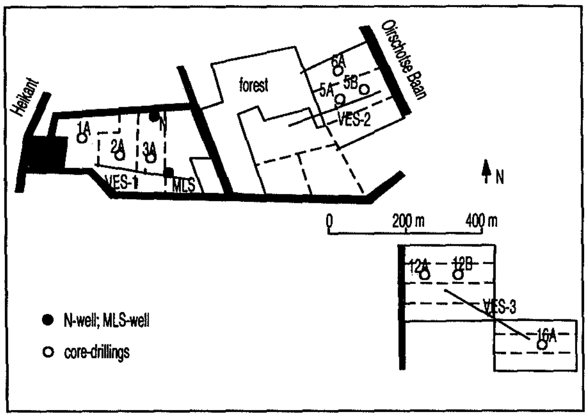


Fig.6.138. The investigations on the farm.

The various situation of the farm parcels implies a variable structure of the topsoils. The parcels near the Heikant have a largely sandy topsoil, which near the farm was covered with manure for long periods. The former inland dunes contain a fine sandy soil. In the stream valley, brook loams and organic sediments were deposited. The shallow subsurface, belongs to a depth of approximately 10 m, to a set of layers (the Nuenen Group), which was deposited during a large part of the Pleistocene Age. The layers of the Nuenen Group have a complicated structure. Below the set of layers, older sandy sediments of a Pleistocene age constitute an upper aquifer, often containing loamy levels and resting on thick clayey layers of the Maassluis and Tegelen Formations, which are of a Lower Pleistocene age. Underneath the confining layers, another aquifer belong to the Oosterhout Formation with a largely Pliocene age. The deep aquifer rests on Tertiary clay layers, beginning at a depth of roughly 200 m below land surface.

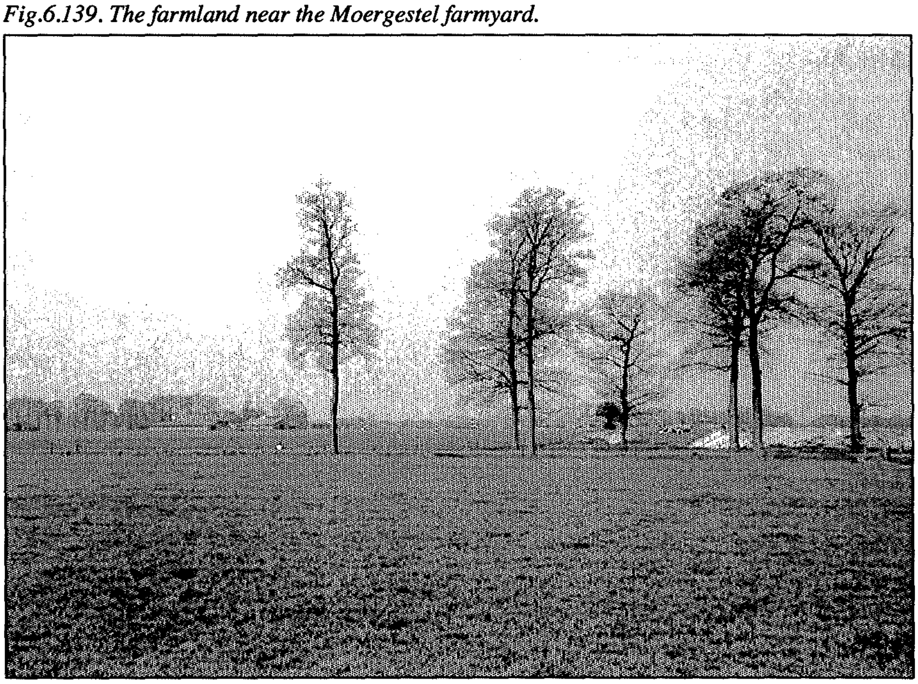
The investigations on the farm (*Fig.6.138*) consisted of a soil survey carried out by Stiboka, based on 118 boreholes. The deeper soil was investigated by means of three VES, a coverage by an EM-31 survey, the drilling of nine cored drillings to a depth of 8 m, in which observation screens were installed and the installation of a cable-tool drilling (N well). Samples were taken, the water levels measured and the wells surveyed. A multi-layer sampler arrangement was used. In 1989, a second series of shallow boreholes was drilled. These boreholes were sampled to analyze again the most shallow groundwater.

The landscape between Moergestel and Heikant (*Fig.6.139*) is half-open, with large trees marking the farms and the main roads. Further to the east, the present pine forest still was heathland in the year 1850, but at a later date, a pine forest was also present. Remnants of former inland dunes, formed by shifting sands, can still be recognized in geomorphology. The land is flat and low, but in many places poplar trees were planted. The Beerze brook valley has long since been in use as meadows and hay fields, the land being open and drained by ditches.

6.5.4.2. Geohydrological structure

The sedimentological analysis of the layers to a depth of 8 m was done on the components of the Nuenen Group, where deposition of soil material has taken

Fig.6.139. The farmland near the Moergestel farmyard.



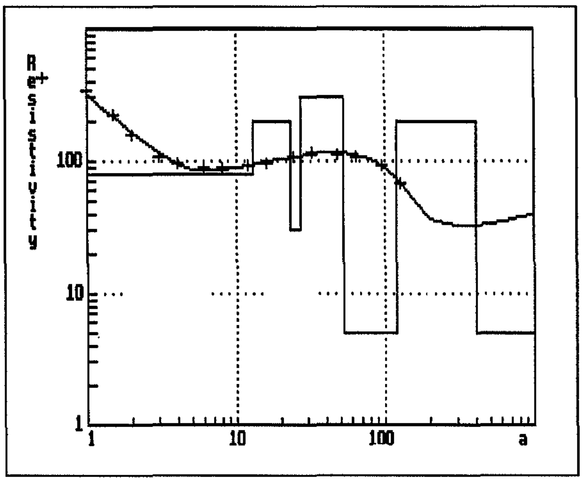


Fig.6.140. VES Moergestel-1.

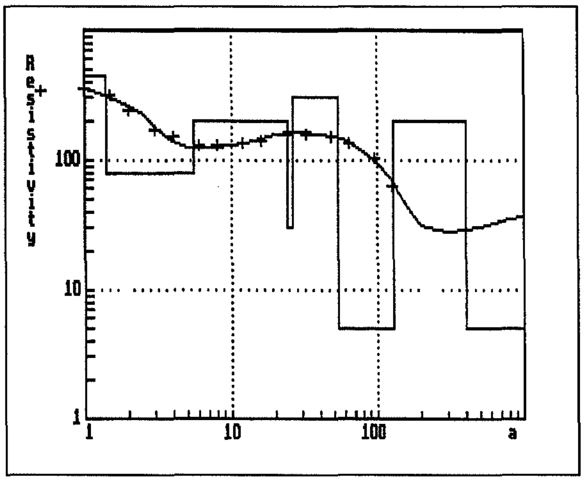


Fig.6.141. VES Moergestel-2.

different forms. The deepest unit, at a depth between 6 and 8 m, was formed by local streams under periglacial conditions, but eolian sediments can also be recognized. Sedimentation probably took place in the Saalian cold period. At a level of 5 m below surface, fluviatile sediments of the second unit, deposited in a warmer period, contain wood remnants and other organic material; the period of deposition was probably the Eemian interstadial period. The deposition of the most shallow third unit in the western parcels consists predominantly of eolian sediments; the local stream valleys were filled in by an influx of sandy material transported by the wind. The local stream, Rosep, was forced to take a more western course, as may be observed from the current situation. However, in the eastern parcel, the deposition by local streams - predecessors of the Beerze - continued in the form of the sedimentation of relatively coarse sandy material to a depth of 1 m, except for the most surficial soil, which consists of loamy deposits.

Less polluted groundwater and possibly also coarse sediments are observed just below the topsoil in the eastern parcels, as can be concluded from the VES interpretation (*Fig.6.140* to *6.142*). The transition between the layers of the Nuenen Group and older Pleistocene formations, which presumably lies at a depth of 10 m, cannot always be derived from the VES. The loamy level, at a depth of 25 m, probably still belongs to the Sterksel Formation, which continues as sand layers to a depth of 50 m. In the western locations, the thick clay layers with the top at 50 m and probably belonging to the Kedichem, Tegelen and Maassluis Formations, are thicker than in the eastern parcel. This is in agreement with general geological evidence (RGD, 1975). Below these lower Pleistocene clay layers, another aquifer consists of sandy sediments of an upper Pliocene age (Oosterhout Formation). However, the interpretation of the lower structure is subject to discussion, because the VES were not long enough.

The EM-31 survey (*Fig.6.143*) indicated the differences in soil conditions; however, also differences in groundwater depth and in composition play an im-

Fig.6.142. VES Moergestel-3.

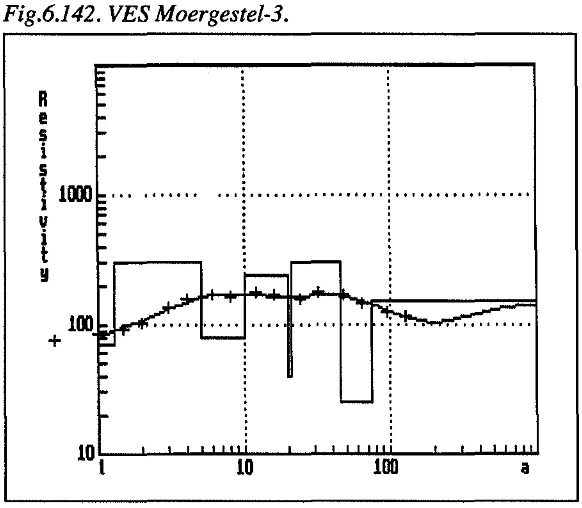
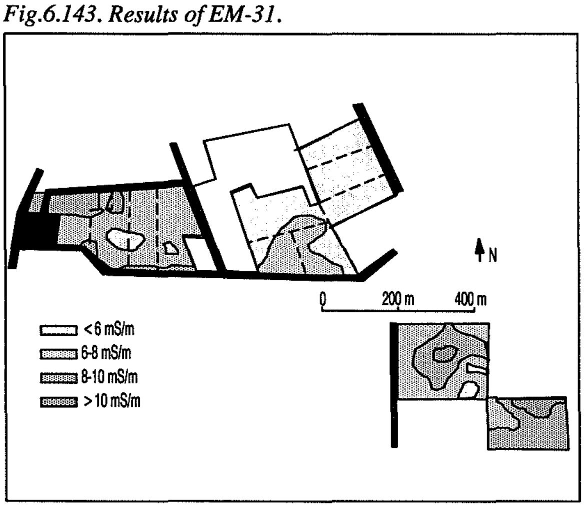


Fig.6.143. Results of EM-31.



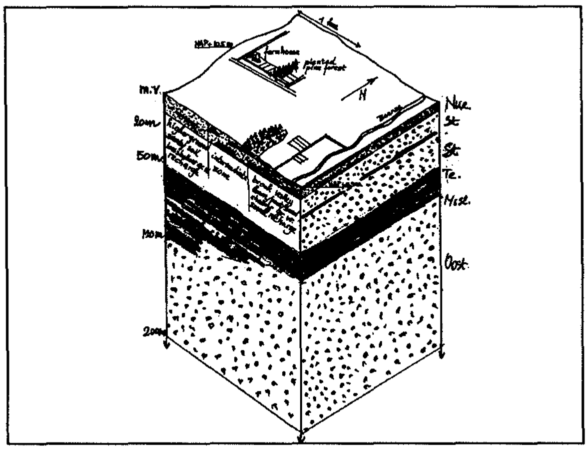


Fig.6.144. Soil structure.

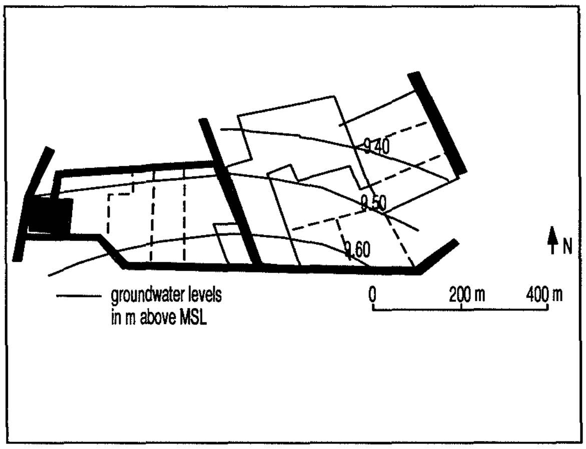


Fig.6.145. Isohypses on 87-04-15.

portant role. Apparently, the groundwater is severely polluted near the farmyard, implying relatively high EM-31 values. The highest EM-31 values were nevertheless observed in the Beerze valley, indicating loamy soils with a shallow groundwater table.

The clay layers, having their top at a depth of 50 m, will practically confine the upper aquifer, such that the shallow groundwater flow patterns will have a base at that depth. The geohydrological situation is summarized in *Fig.6.144*.

With the help of water level measurements in the boreholes on 1987-04-15, a map of groundwater contours (*Fig.6.145*) was composed. The flow direction is from south to north, which agrees with the regional pattern (DGV-TNO, Groundwater Map). The gradient in groundwater heads is 1:1250. The curvilinear pattern indicates a situation near the water divide between two draining streams.

From the measured tritium levels in the N well (*Fig.6.146*), a vertical groundwater percolation can be derived. Assuming that D=50 m, the interpretation results in a downward groundwater velocity at the groundwater table of I/p=0.91 m·a^{-1}, implying that the groundwater recharge is I=320 mm·a^{-1}, for p=0.35. The multiplication factor of f=1.15 corresponds to the expected value in rainwater of f=1.14.

6.5.4.3. Peculiar environmental phenomena

The analysis of the chemical compounds in samples from the shallow boreholes taken on 19870417 resulted in unexpectedly low values (*Fig.6.147*), especially at parcels 3 and 4. The total application of nitrogen compounds in the years before 1987 was 730 kg·ha^{-1}, divided in 430 kg·ha^{-1} given as fertilizer, 175 kg·ha^{-1} as manure slurry and 125 kg·ha^{-1} as natural manure. The average concentration of all observed

Fig.6.146. ^3H level in the N well.

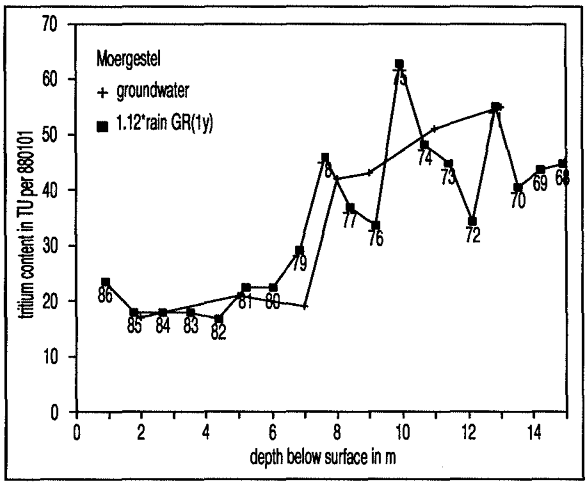
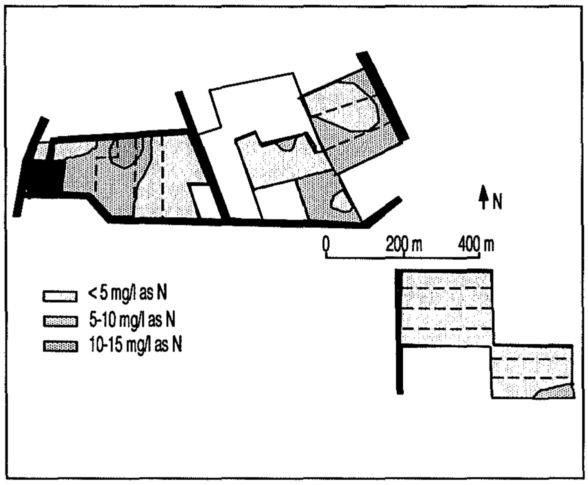


Fig. 6.147. N-concentrations shallow groundwater (in mg/l as N)



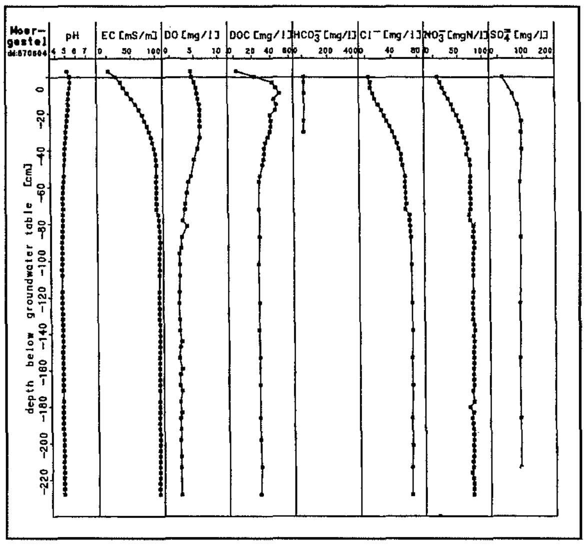
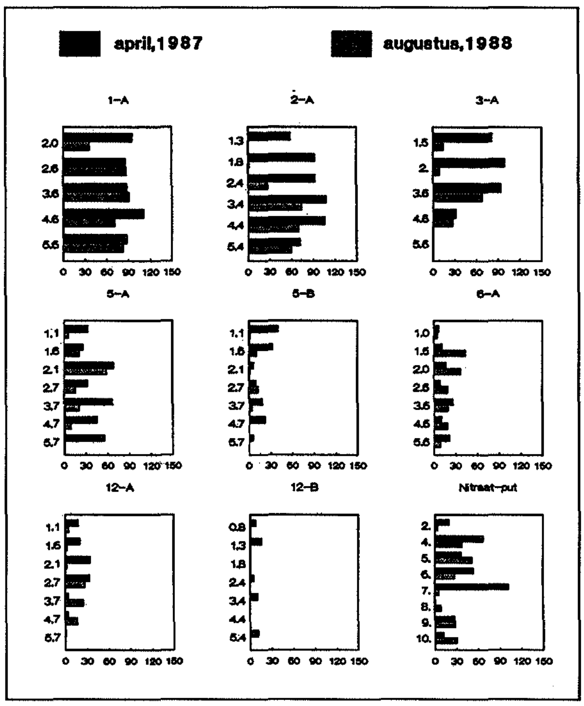


Fig.6.148. Results of the multi-layer sampler on 87-06-04.

nitrate concentrations in the shallow groundwater is 3.7 mg·l^{-1} (as N), representing a total of 101 observations. At a groundwater recharge of 320 mm·a^{-1}, as estimated from the tritium profile, it can be computed that the average annual leaching is 12 kg·ha^{-1}, representing 1.7% of the total dose. The estimated leaching of nitrogen compounds computed with the NLOAD model (Van Drecht, 1989) constitutes 7.5% of the total dose. The observed leaching of nitrogen compounds is far less than the predicted leaching, whereas for the other test farms, the measured and the predicted values show a reasonable similarity. In

Fig.6.149. N concentrations in deeper groundwater.



the saturated groundwater of the parcels 3 and 4, with a sandy soil and groundwater tables, corresponding to GT VI, the expected concentrations are approximately 35 mg·l^{-1}, whereas the measured values were in the order of 2 mg·l^{-1}. Hence, the agreement is even far less when only the parcels with deep groundwater levels are considered.

If the results from the cored drillings (*Fig.6.149*) are taken, it appears that the measured values correspond to values predicted using the NLOAD model. The place of recharge and groundwater travel times may be estimated from hydrological observations. In comparing the expected nitrate concentrations (not the measured values) for the upper saturated groundwater to corresponding values in deeper groundwater, the reduction rate may be estimated. The conclusion is that:

80% of the observations in deeper screens correspond to, or are even higher than the predicted values;

20% of the observations indicate a reduction of approximately 50%;

Hence, the reduction in groundwater of the saturated zone is almost negligible.

In the evaluation of the deviating chemical composition in the shallow groundwater, relevant questions are whether the observed values are representative with regard to the actual soil situation at the moment of sampling and, if so, whether the investigated farm represents a special situation. In other words: Are the measured values correct and if they are correct, do they represent a natural situation? Three arguments support an affirmative answer for both cases:

1. Low values observed in boreholes agree with low values observed at the top of an almost simultaneous MLS series (*Fig.6.148*).
2. The deviating observations are spatially related. Nitrate, chloride and sulphate concentrations were relatively low in the same area (compare *Fig.6.147* and *6.150*)
3. Incorrect laboratory analyses are less likely because the samples from boreholes were analyzed by RIVM and the MLS samples by another laboratory (Lab. Oost).

Additional measurements on the test farm give further insight in the shallow groundwater composition on the farm.

- From the same borehole, where the first MLS series of samples was taken on 1987-06-04, two other series of samples were taken on 1987-11-19 and again on 1988-05-27 (*Fig.6.151* and *6.152*).

  In the spring of 1989, a smaller set of boreholes was drilled on the farm, which were sampled. The results of the 1989 sampling are represented in *Table 6.39.*

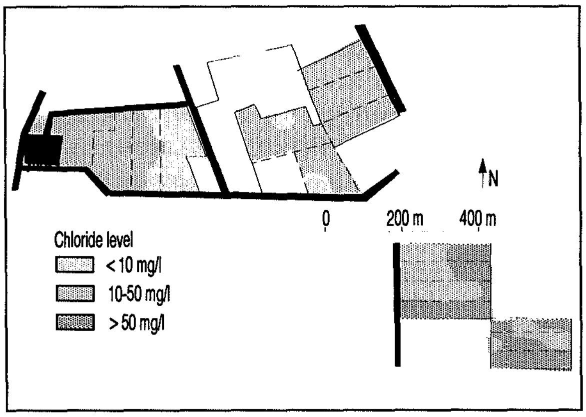


Fig.6.150. Cl⁻ concentrations in shallow groundwater on 1987-04-17.

The conclusion from *Table 6.39* is that values were determined in the spring of 1989, which again are in agreement with the values to be expected in the given situation (according to the NLOAD model). However, the two other MLS series confirm the results of the earlier measurements. In the figures, a time scale can be imagined, which is based on a vertical percolation of 0.9 $m \cdot a^{-1}$ as derived from the tritium measurements and assuming that the same vertical velocity also holds for the unsaturated zone. The following conclusions can be drawn:

1. From 1985 to spring 1987, low nitrate concentrations percolated to the groundwater of the saturated zone.
2. The incoming low concentrations were mixed with the already present higher concentrations.

A possible explanation of the observed phenomena could be the occurrence of heavy frost periods in the years concerned, when the shallow soil was also frozen. This might result in dissolved minerals from the shallow soil freezing out (and being removed) and the destruction of biological life in the topsoil. A visible effect was the destruction of the existing grass cover, necessitating renewed seeding. The restoration of biological life in the shallow soil will have claimed many of the incoming minerals.

6.5.5. The Bavel test farm

6.5.5.1. Situation and investigations

The land around the village of Bavel (*Fig.6.153*) is slightly undulating. Low elevations have been named 'berg'. Within the region, groups of farms form small neighbourhoods, where the farmyards are surrounded by tall trees. Farming has been an important activity here for a long time, but the clayey soil has also been used for brick-making. A number of brickworks were dispersed over the area, but most of them are now abandoned. The land is drained by a number of small streams. The 1850 topographical map (*Fig.6.154*), already shows the present land structure. However, the many patches with deciduous forest have lost much of their importance. Moreover, the landscape has been changed by the construction of a highway, transporting the east-west traffic in that part of the country.

From a geological point of view, the Bavel subsurface is relatively old. Most of the Netherlands territory overlies a subsiding basin with thick layers of

Fig.6.151. MLS observations for the same borehole on 871119; Moergestel.

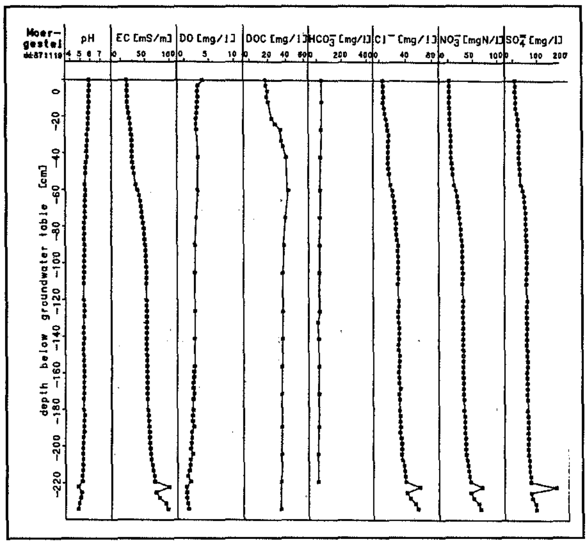


Fig.6.152. MLS observations for the same borehole on 880527; Moergestel

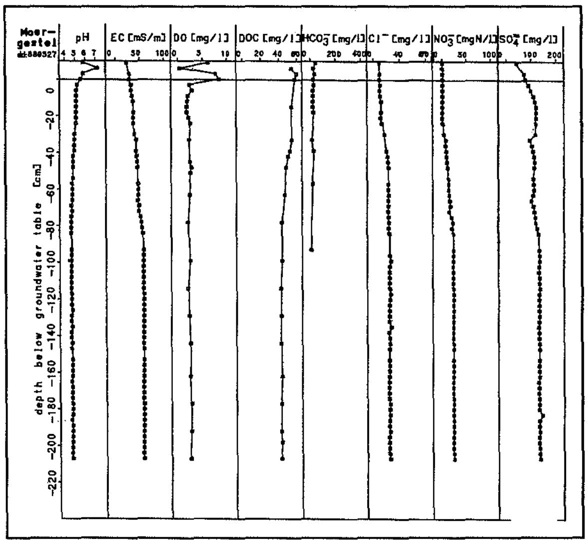


Table 6.39. Average nitrate concentrations (mg·l^{-1}, as N) of samples taken in 1989-04 from boreholes of the Moergestel farm.

Parcel 1:	3 samples: 65 mg·l^{-1};	Parcel 2:	2 samples: 50 mg·l^{-1};
Parcel 3:	2 samples: 18 mg·l^{-1};	Parcel 4:	2 samples: 61 mg·l^{-1};
Parcel 5:	2 samples: 2 mg·l^{-1};	Parcel 6:	2 samples: 5 mg·l^{-1};
Parcel 8:	1 samples: 1 mg·l^{-1};	Parcel 9:	2 samples: 34 mg·l^{-1};

Pleistocene sediments, but the west part of North Brabant belongs to the structurally rising body of the Brabant Highlands, having its centre in Belgium. Relatively thick strata were deposited at the beginning of the Pleistocene period, but after that time the rivers Rhine and Meuse left the area and sedimentation came to a halt, except for a thin layer of Upper Pleistocene cover sands. For this reason, the Lower and Middle Pleistocene Formations of Kedichem and Tegelen are near land surface at the test farm. These formations contain many clayey and loamy components on the test farm, implying the presence of shallow clay layers below a thin topsoil of cover sands. The Tegelen Formation and the underlying Maassluis Formation, the latter consisting of marine clayey and loamy deposits, occupy the upper 100 m of subsurface; they rest on a sandy aquifer of an Upper Tertiary age.

The investigations on the farm (*Fig.6.155*) consisted of a soil survey based on 109 boreholes and carried out by Stiboka. The deeper soil was investigated by three VES and a coverage by EM-31 measurements. As the manual drilling of cored borings seemed to pose difficulties because of the clayey soil, it has largely been omitted. However, a cable-tool drilling was made, in which observation screens were installed from which samples were taken. The soil did not permit the installation of a multi-layer sampler.

The test farm (*Fig.6.156*) is situated in the area, Bolberg, and the farmland is indeed slightly higher than the surroundings. During a recent project of land improvement, the parcels were enlarged and the natural water courses canalized. The land was levelled down and, where necessary, a system of tile drainage was installed. The test farm is laid in permanent pasture, except for some parcels, where maize is grown for cattle fodder.

6.5.5.2. Geohydrological structure

The presence of clay layers at a shallow depth, notably in the eastern parcels, can also be derived from the VES data (*Figs.6.157 - 6.159*). At a depth of less than 10 m, a sandier zone is present in the shallow subsurface. The shallow sandy topsoils consist of cover sands of the Twente Formation; the shallow clay layer and the more sandy zone to a depth of 10 m probably belong to the Kedichem Formation and the layers under it to the Tegelen Formation. The loamier trajectory down to a depth of 14 to 20 m belongs, at least partly, to the Tegelen Formation, grad-

Fig.6.153. Situation of the Bavel test farm

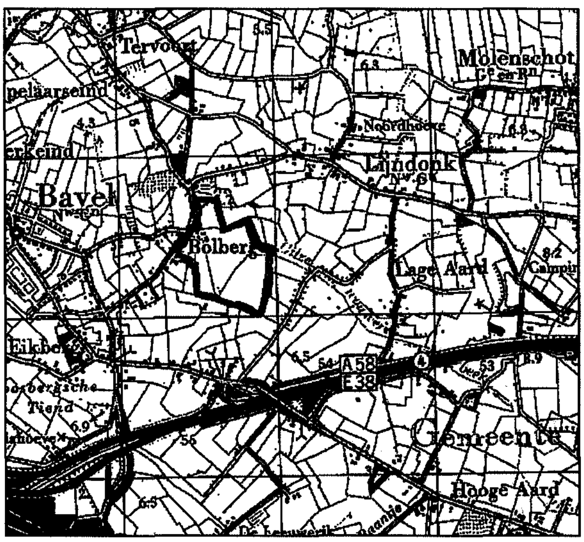


Fig.6.154. Topographical map of 1850.

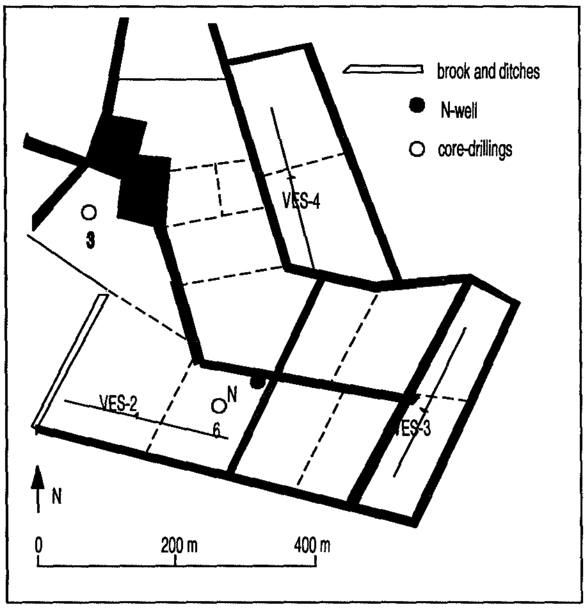


Fig.6.155. The investigations on the farm.

ually continuing as the Maassluis Formation, consisting of an intercalation of loamy and fine sandy layers. The deeper subsurface cannot be further detailed on the basis of the VES carried out.

The results of the EM-31 survey (*Fig.6.160*) are not very decisive with regard to differences in soil conditions. The relatively high values indicate the presence of shallow clay layers. The clay layers are probably the most shallow and the thickest in the zones where the highest EM-31 values of more than 25 $mS{\cdot}m^{-1}$ were observed - on the east side of the farm parcel, where the cover sands are thinly developed. The geohydrological situation of the Bavel farm is summarized in *Fig.6.161*.

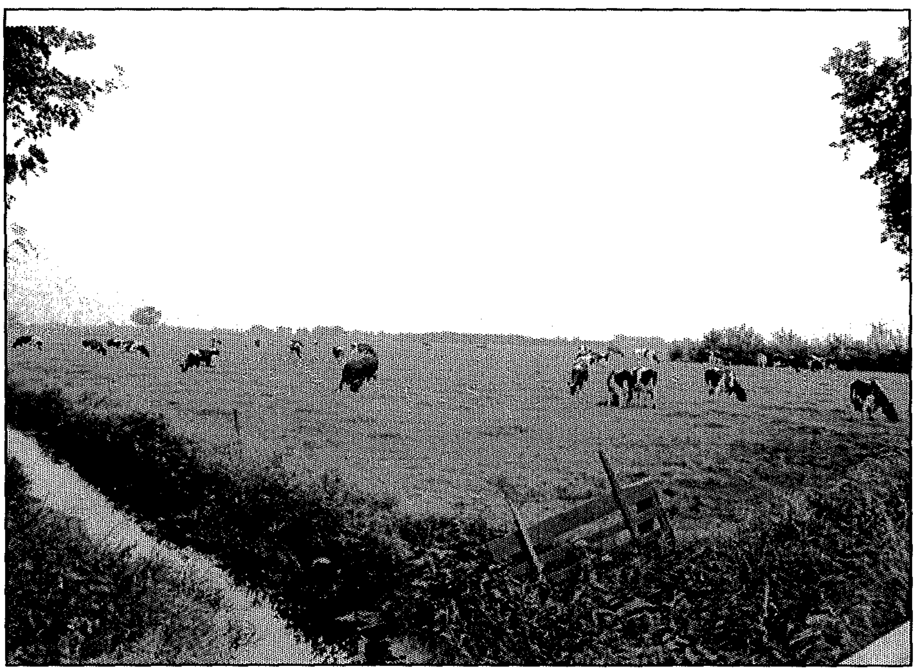
Groundwater isohypses could not be composed on the basis of level measurements on the farm. It may be assumed that the flow is roughly from south to north (DGV-TNO, Groundwater Map of the Netherlands). The water course on the test farm (Gilze-Wouwer Loop) strongly drains the shallow groundwater, but still, a part of the rainfall excess percolates to deeper layers. On the basis of water samples collected from the cable-tool drilling, it was possible to compose a tritium profile for the shallow groundwater (*Fig.6.162*). The interpretation, based on an aquifer depth of D=100 m, yielded the following results:

f= 1.14 (multiplication factor);

I/p= 0.44 $m{\cdot}a^{-1}$, with I=155 $mm{\cdot}a^{-1}$ at p=0.35.

The multiplication factor corresponds to the expected regional value for the local rainfall. The computed groundwater recharge is far lower than the estimated local rainfall excess, implying that a significant part of the rainfall excess is discharged by a surficial drainage of the shallow groundwater. The tile drainage installed will discharge much of this water.

Fig.6.156. The farmlands on the Bolberg.



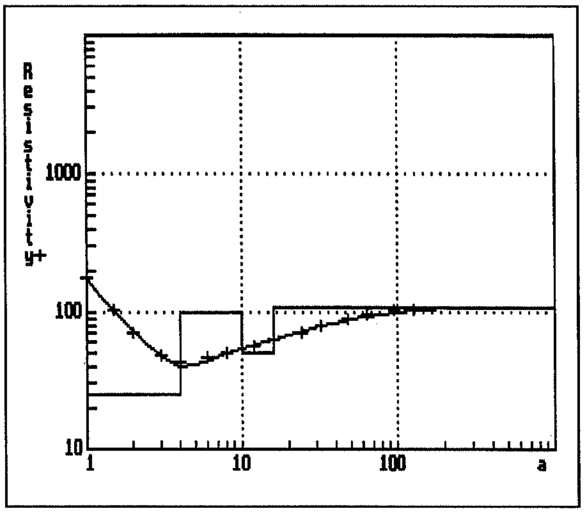


Fig.6.157. VES Bavel-2.

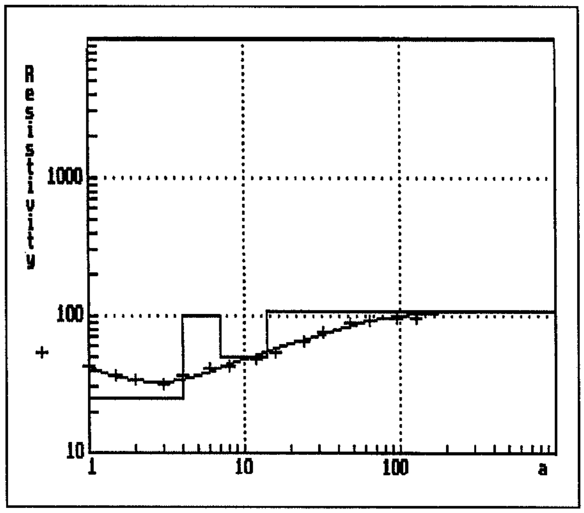


Fig.6.158. VES Bavel-3.

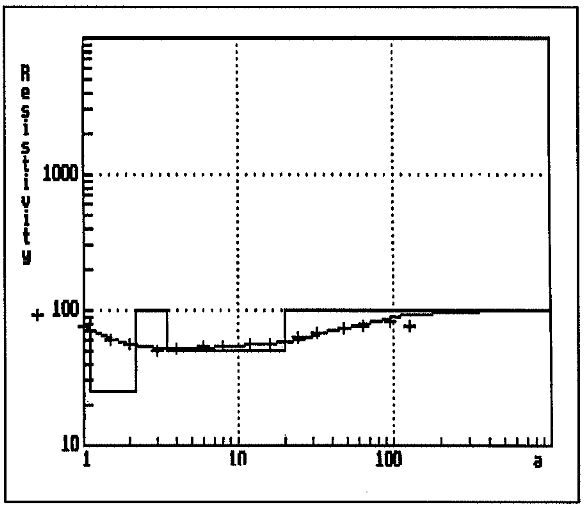


Fig.6.159. VES Bavel-4.

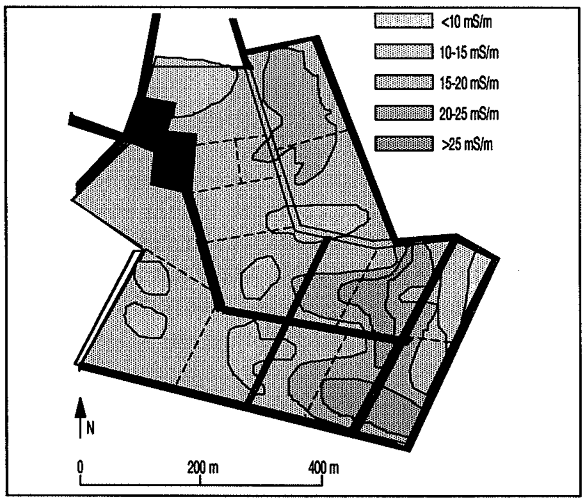


Fig.6.160. Results of EM-31.

Fig.6.161. Soil structure.

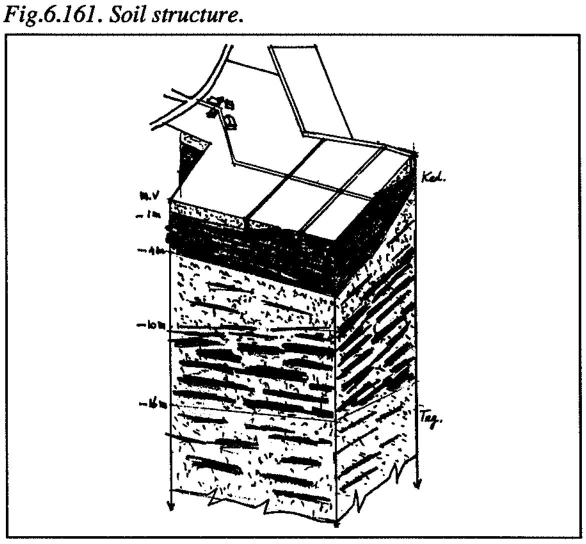
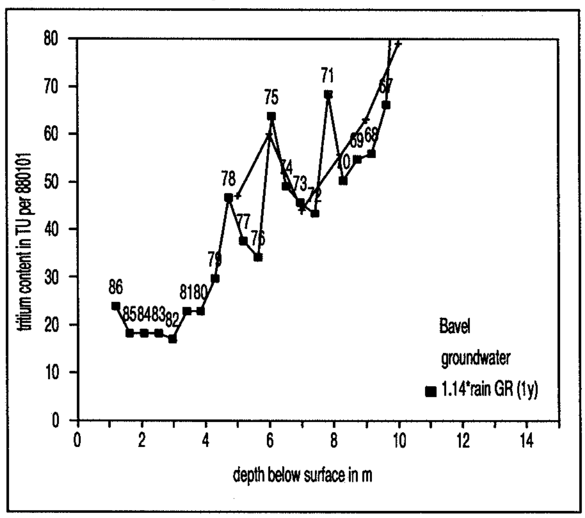


Fig.6.162. ^3H levels of the N well.



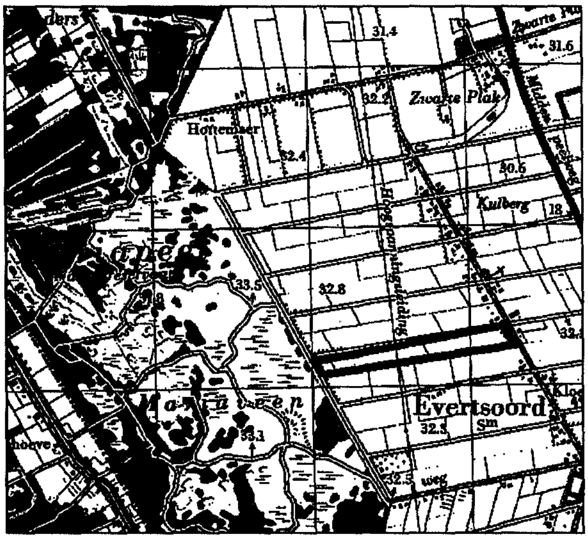


Fig. 6.163. Situation

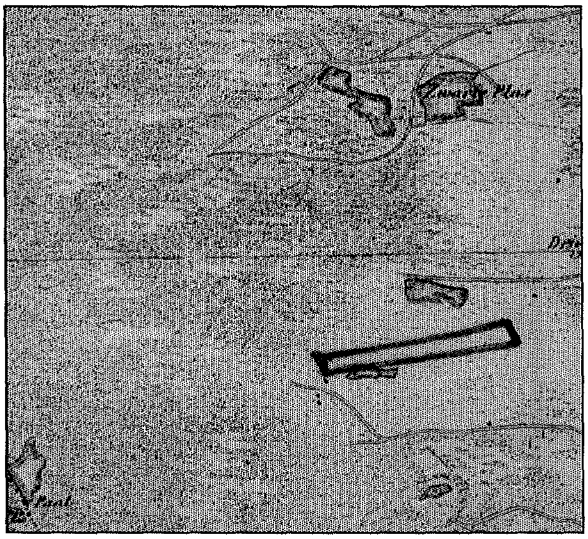


Fig. 6.164. Top. Map 1850

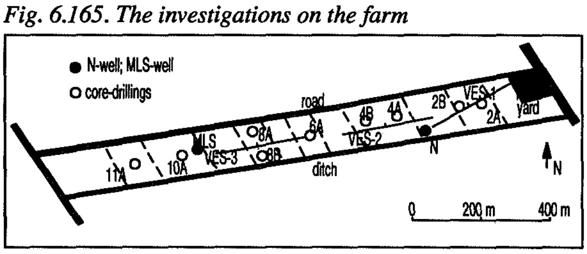
6.5.6. The Sevenum test farm

6.5.6.1. *Situation and investigations*

The Sevenum farm parcel (*Fig.6.163*) is situated in the central zone of the Peel area. On the west side the farmland is bordered by the former Peel raised bog, which now a nature reserve, where low bushes, grass and sphagnum moss grow and where the soil is still swampy. The boundary between the nature reserve and the farmland is formed by the Defensiekanaal, dug for military reasons in the 1930s. The former peat layers were largely excavated roughly 100 years ago by the Van der Griendt company, which extracted the peat layers situated in the central Peel area between the present Griendtsveen in the north and Helenaveen in the south.

The remaining wasteland of the Peel area was reclaimed for agriculture in the first half of this century, the land of the test farm only in the 1950s. Presumably, the peat layers on the farmland were not thick, yet the 1850 topographical map (*Fig.6.164*) indicates swampy areas near the present farmland. In the reclamation, the topsoil was reworked such that a sandy soil remained with many organic components.

Fig. 6.165. The investigations on the farm



The field investigations (*Fig.6.165*) consisted of a soil survey based on 70 boreholes carried out by Stiboka. The deeper soil was investigated by means of three VES, a full coverage by EM-31 data, the drilling of seven cored drillings to a depth of 8 m, in which observation screens were constructed, and the installation of a cable-tool drilling. Samples were taken and the water levels were measured. A multilayer sampler was temporarily installed and used.

The upper sand layers of the deeper subsurface consist of cover sands of the Twente Formation, which were partly reworked by local streams. From a depth of roughly 10 m, the Veghel Formation, consisting of relatively coarse sands, continues to a depth of roughly 20 m, where it rests on loamy and sandy layers belonging to the Tegelen Formation. It may be expected that the Tegelen clay layers underneath the nature reserve will be even more important because the limited transport capacity of the shallow subsurface is the main factor initiating swampy conditions and peat growth on land surface. Between a depth of 20 m and approximately 50 m, another series of sandy layers, belonging to Lower Pleistocene and Upper Tertiary formations, constitutes a deeper subaquifer. The base layer of clayey and loamy sediments at a depth of roughly 50 m below surface belongs to Tertiary Formations.

The land has been parcelled in oblong and regular stretches of land in the direction of the Defensiekanaal. The land is laid in permanent pasture, alternating with maize parcels. Modern farm buildings form the only elevated elements in the open land (*Fig.6.166*).

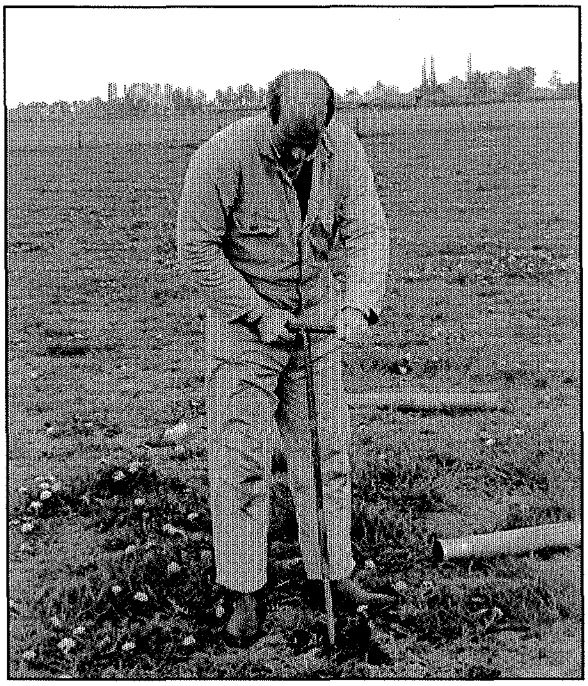


Fig. 6.166. Auger drilling in Sevenum.

6.5.6.2. Geohydrological structure

The sedimentological analysis of the layers, down to a depth of 8 m, did not result in the conclusion of a strongly differentiated soil structure. The layers were originally deposited by the wind and later reworked by small streams. In the western part of the parcel, organic plant residues were observed at a depth of roughly 5 m, which probably were deposited during the Eemian interstadial in a warmer period.

A notable feature of the interpretation of the VES (*Figs.6.167-6.168*), is the relatively sharp transition at a depth of roughly 10 m, where sandy layers with a low resistivity rest on sand layers having a resistivity that is twice as high. This transition most probably marks the boundary between groundwater recharged from the former wastelands and groundwater recharged from the later agricultural land and transporting minerals derived from the application of fertilizer. The presence of Tegelen clay layers at a depth of 20 m can only be derived from the interpretation of VES-3, being located on the west side of the parcel (*Fig.6.167*). The Tertiary base begins at a depth between 50 m and 55 m.

The EM-31 values measured on the farm (*Fig.6.170*) do not show large differences, which is in agreement with the relatively uniform soil conditions, including the depth of the groundwater table, already observed at the Stiboka soil survey.

Evidently, the sandy subsurface in the east part of the parcel constitutes a single aquifer down to the Tertiary base; the Tegelen loam layers in the west might divide the subsurface in two separate subaquifers. The hydrological situation will have differed in the situation before reclamation, if compared to the later flow patterns. Both geohydrological situations are summarized in *Fig.6.171*.

A vertical groundwater percolation can be derived from the measured tritium levels in the N well (*Fig.6.172*). Assuming that D=55 m, the downward groundwater velocity in the groundwater table is equal to $I/p=1.03$ m·a^{-1}, implying that the groundwater recharge is $I=360$ mm·a^{-1}, for $p=0.35$. The estimated recharge can be higher than the local rainfall excess because of the application of intensive sprinkling by the farmer. The multiplication factor of $f=1.28$ corresponds to the expected regional value in rainwater, which is $f=1.25$.

Water levels were measured in the boreholes on 1987-04-27 and after surveying, a map of groundwa-

Fig.6.167. VES Sevenum-3.

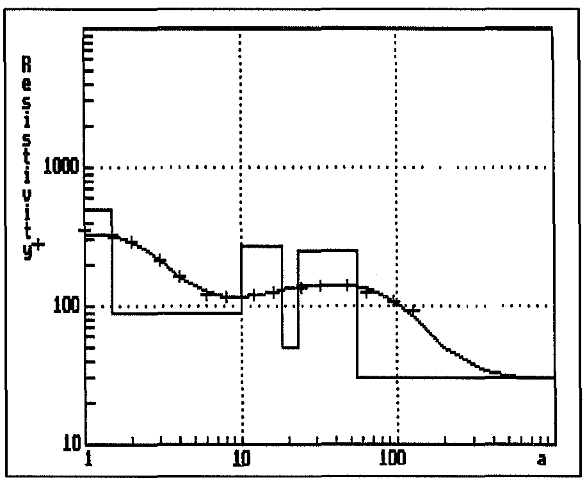
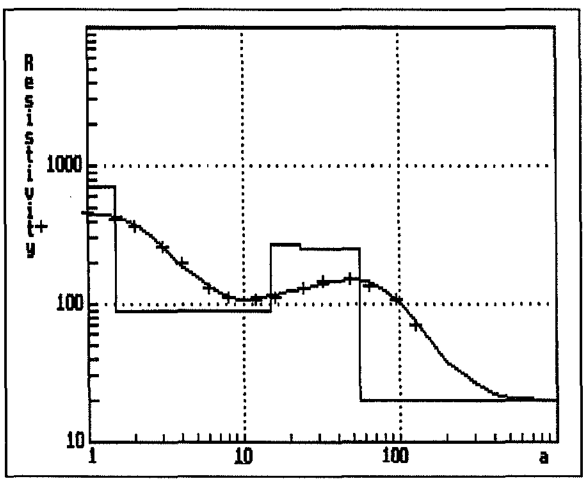


Fig.6.168. VES Sevenum-2.



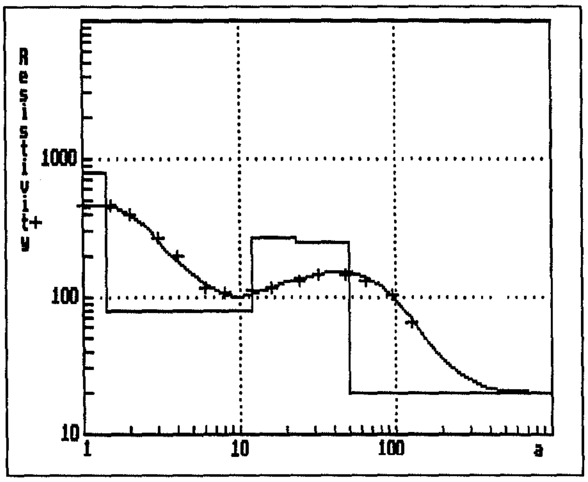


Fig. 6.169. VES Sevenum-1

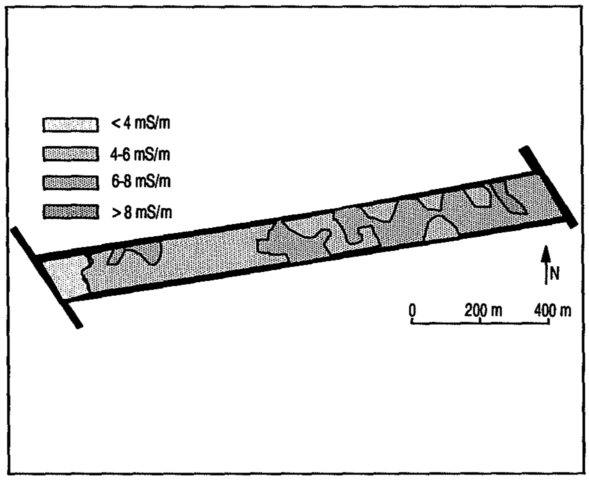


Fig. 6.170. Results EM-31 (mS/m)

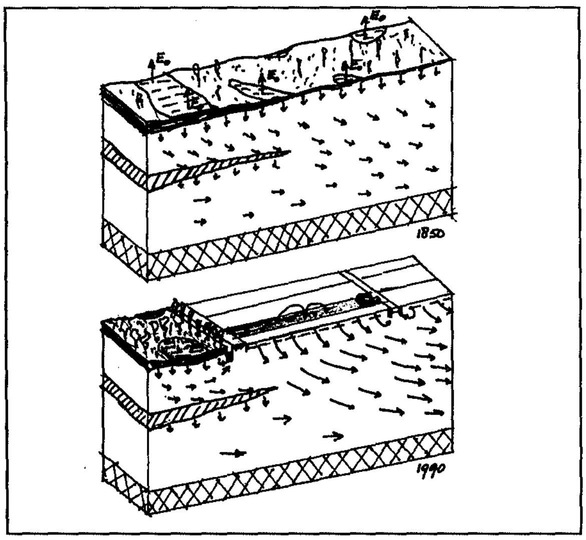


Fig. 6.171. Flow patterns in 1850 and now

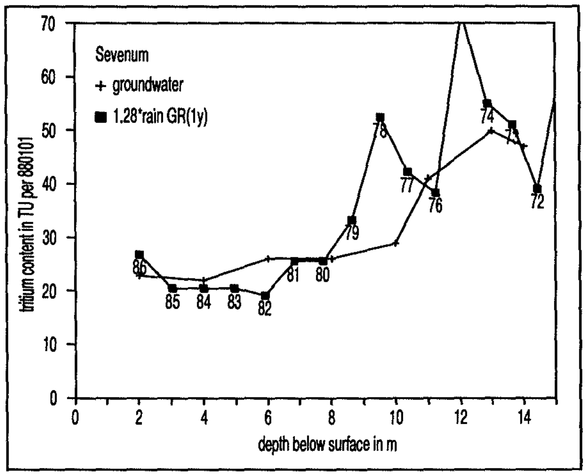


Fig. 6.172. ^3H contents N-well

ter contours (*Fig.6.173*) was composed. The flow direction is from west to east, which agrees with the regional pattern (DGV-TNO, Groundwater Map of the Netherlands). The irregular pattern near the natural reserve is probably caused by small local deviations in the patterns of soil conditions, leading to a slightly irregular groundwater recharge.

6.5.6.3. The environmental situation

Also at the Sevenum location, the nitrate concentrations in the shallow saturated groundwater sampled from 65 boreholes on the farm strongly deviate from the expected values (*Fig.6.174*). The total application of nitrogen compounds in an average year before 1987

Fig.6.173. Groundwater isohypses on 1987-04-23.

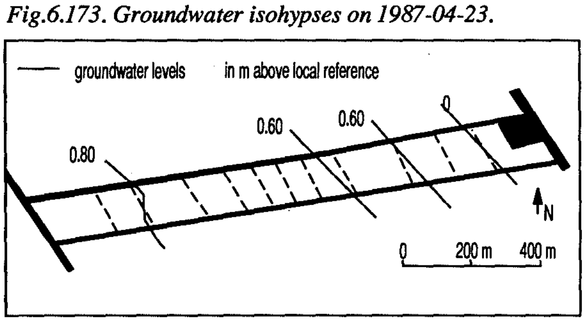
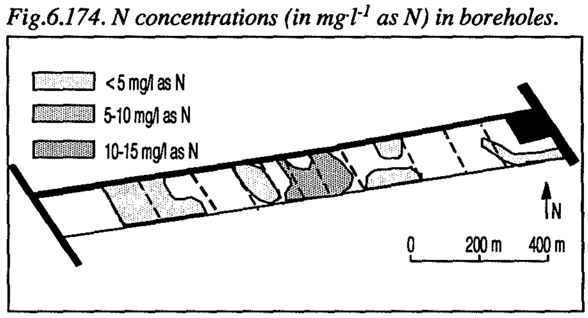


Fig.6.174. N concentrations (in mg·l^{-1} as N) in boreholes.



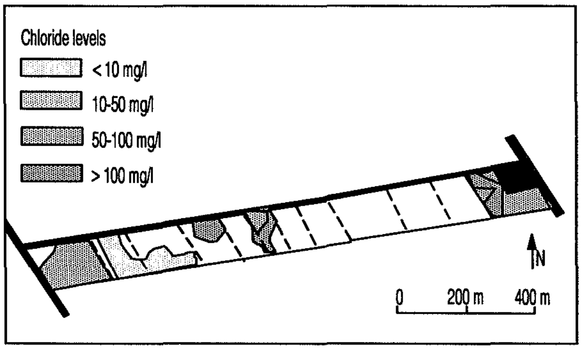


Fig.6.175. Chloride concentrations in boreholes.

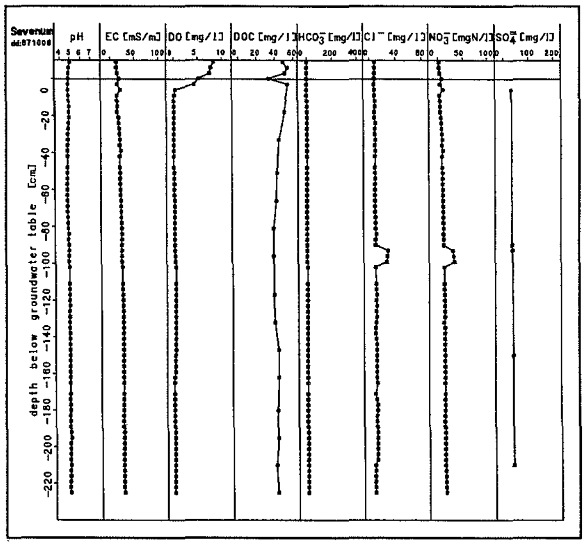
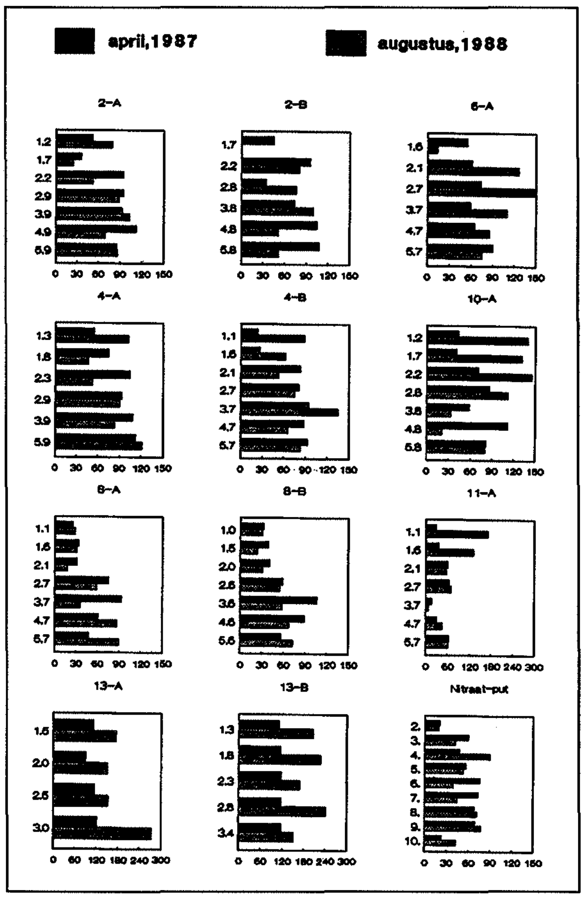


Fig.6.176. Results multi-layer sampler.

was 725 kg·ha^{-1}, divided in 455 kg·ha^{-1} given as fertilizer, 125 kg·ha^{-1} as manure slurry and 145 kg·ha^{-1} as natural manure. In the saturated groundwater of parcels with a sandy soil and groundwater tables corresponding to GT V to VII, the expected concentrations would be approximately 30 to 50 mg·l^{-1}, whereas the measured values are in the order of magnitude of 5 mg·l^{-1}. The average concentration of nitrate in the shallow groundwater is 7.2 mg·l^{-1} (as N). At a groundwater recharge of 360 mm·a^{-1}, like estimated from the tritium profile, it can be computed that the average annual leaching is 26 kg·ha^{-1}, representing 3.6% of the total dose. The leaching of nitrogen compounds estimated from the NLOAD model constitutes 20% of the total dose. Hence, the observed leaching of nitrogen compounds is far less than the predicted leaching. For the other test farms, except Moergestel, measured and predicted values are in the same range. Aspects of the groundwater composition are shown in *Table 6.40.*

Fig. 6.177. N-concentrations deeper groundwatr



At the Sevenum farm, also the MLS observations (*Fig.6.176*) are lower than expected, but the samples drawn from the cored drillings show average nitrate concentrations which are even slightly higher than the expected values (*Fig.6.177*). The differences become apparent from *Table 6.40*, where the average values measured at various observations are represented. In *Table 6.40*, also other parameters of the groundwater composition are indicated, showing that in the case of the MLS, the chloride concentrations are unexpectedly low. Nevertheless, the observations with the multi-layer sampler are corrobated by data from the shallow boreholes for the Cl^- concentrations (*Fig.6.175*), which, near the location of the MLS, indicate a zone with values lower than 10 mg·l^{-1}. The variation in chloride concentrations in the shallow saturated groundwater is large, ranging from less than 10 mg·l^{-1} to more than 100 mg·l^{-1}. The values measured in shallow boreholes, constructed and sampled in 1989, again resulted in values (Boumans, 1990) deviating from the earlier measurements. The average values, observed in 1989, are

Table 6.40. Average values for groundwater composition on the Sevenum farm. Average values and concentrations in mg·l^{-1} (nitrate as N) except pH and EC mS.m^{-1})

No.	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	pH	cond.
1	52	7.2	94	16				34.8	2.5	5.0	116.5
2	9.5	10.6	35		20	7.0	4	7.3			
3	46	68	70	11				35.3	1.0	4.8	94.2
4	33	35	136	01				12	4.7	4.4	77
5		73									

1= boreholes-8704; 2=MLS-8710; 3=suction-corer wells-8704;
4= N well (screens 7-14 m-mv); 5= boreholes-890428(19 obs.)

also represented in *Table 6.40*. The peculiar environmental situation on the farm will not be discussed in full detail.

6.5.7. Tritium data of Groundwater Monitoring Stations

6.5.7.1. North-west Brabant

For a long time, the land around the city of Breda has been used for traditional agriculture. The rest of the sandy region of north-west Brabant was largely covered by vast heathlands drained by local streams, converging near Breda. In the western Zoom area, the Brabant highlands were eroded by the sea, causing a relatively steep slope towards the River Scheldt and the existence of perched groundwater tables in the Zoom area. Much of the land has been reclaimed for dairy farming and intensive animal husbandry is in strong development. In the Zoom subregion, a large part of the land is covered by pine forests. But also elsewhere, smaller forests are present. The system of streams, the 'Chaamse beken', together with the stream valleys, is still of natural value.

The local subsurface contains less pervious layers at a shallow depth. Consequently, the shallow soil often cannot transport the rainfall excess, implying surface runoff features and the existence of natural ponds, called vennen. Only at greater depths, does the subsurface contain sandy layers of the Lower Pleistocene and Pliocene Ages, which constitute a confined upper aquifer system. For the interpretation of the tritium data from LMG wells (*Table 6.41*), D=150 m is taken. Average results for the groundwater recharge are for cases without surficial discharge

grassland :	n=4;	$I/p_{avg.}$=0.77 m·a^{-1};	$I_{avg.}$=269 mm·a^{-1};
arable land:	n=1;	$I/p_{avg.}$=0.95 m·a^{-1};	$I_{avg.}$=334 mm·a^{-1};
forest areas:	n=2;	$I/p_{avg.}$=0.79 m·a^{-1};	$I_{avg.}$=277 mm·a^{-1};

6.5.7.2. Central Valley (Meierei)

The land in the northern zone of the Central Valley (Meierij van Den Bosch) has always formed part of a variable landscape. Apart from the river clay belt in the north, the sandy areas were divided in low-lying stream valleys, covered by a swamp vegetation and higher grounds with a heather vegetation, or even moving sand dunes. Old agricultural lands were reclaimed in the transition zone and have been in use for a long time. At present, much of the land is laid in pasture for dairy farming. Parts of the former wetlands were planted with poplar trees. The Drunensche Duinen still consist of bare dunes.

The subsurface contains the less pervious layers of the Nuenen Group. The greatest depth of these covering layers is roughly 30 m, found near the village of Best. The so-called Brabant Loam consists of a relatively thick loam layer, which may be present over large areas and which is part of the upper zone of the Nuenen Group. Below this set of layers, an upper aquifer system of coarse sandy layers reaches a depth of roughly 100 m below surface. For the interpretation of the data from LMG wells (*Table 6.42*), D=100 m is taken. A number of results indicate values of recharge less than expected, leading to the interpretation of surficial runoff components, reducing the infiltration to deeper layers. Average values of the recharge for cases without surficial discharge are:

grassland :	n=2;	$I/p_{avg.}$=0.88 m·a^{-1};	$I_{avg.}$=308 mm·a^{-1};
arable land:	n=1;	$I/p_{avg.}$=0.95 m·a^{-1};	$I_{avg.}$=346 mm·a^{-1};

6.5.7.3. Central Valley (Kempen)

The Kempen region was formerly covered by vast heathlands, where almost no one lived. The land was drained by a few local streams and by an important groundwater flow. After the introduction of fertilizer, the land was reclaimed for dairy farming and some arable land. At present, intensive animal husbandry is

Table 6.41. Tritium observations in LMG wells in north-west Brabant (1-83=upper screen, 1983; 3-83=lower screen, 1983) (mS.m^{-1})

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} m·a^{-1}	I_{avg} mm·a^{-1}
135	oosterhout	arable	94	1	0.45	158
136	dorst	forest	79	46	0.75	261
139	oosteind	grass	1	8	0.79	275
140	rijen	grass	46	1	(1.76)	(617)
141	halsteren	arable	1	1	und.	und.
142	wouw	arable	1	1	und.	und.
143	berg.o.z.	forest	und.	und.	und.	und.
144	schijf	forest	72	74	0.83	291
146	achtmaal	grass	32	13	0.83	292
147	rijsbrg.	grass	37	1	0.83	292
148	ettenleur	unknown	30	49	0.56	195
149	breda	unknown	55	18	0.60	212
150	b-nassau	grass	37	und.	0.62	217
151	gilze	arable	43	1	0.95	334

the most important type of farming. Relatively large areas are still covered by heather, being much-valued nature reserves at present. Many former wastelands were planted with pine forests. Important industrial activities have developed during this century and have been growing ever since. The area around Eindhoven is densely populated. Around the village of Budel, a large area has been affected by air pollution from the local zinc factory. A large part of the subsurface contains sandy layers of a Middle Pleistocene Age, down to a variable depth. However, on the northern fringes, the Nuenen Group was deposited, which may confine the upper aquifer.

For the interpretation of the data from LMG wells (*Table 6.43*), D=80 m is taken. LMG well no.113 was sampled twice, in 1982 and again in 1983, with comparable results. Average values of the recharge for cases without surficial discharge are:

grassland :	n=1;	$I/p_{avg.}$=0.87 m·a^{-1};	$I_{avg.}$=305 mm·a^{-1};
arable land:	n=2;	$I/p_{avg.}$=0.82 m·a^{-1};	$I_{avg.}$=286 mm·a^{-1};
forest areas:	n=6;	$I/p_{avg.}$=0.69 m·a^{-1};	$I_{avg.}$=242 mm·a^{-1};

Table 6.42. Tritium observations for LMG wells in the north part of the Central Valley, de Meierij van Den Bosch (1-83= upper screen, 1983; 3-83= lower screen, 1983)

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} m·a^{-1}	I_{avg} mm·a^{-1}
94	kaatsh.	forest	91	1	0.64	224
95	nuland	grass	70	30	0.90	315
97	haaren	arable	64	1	0.46	162
96	lith	grass	66	5	0.86	302
98	venkant	grass	1	1	und.	und.
99	denbosch	built-up	57	68	1.16	405
102	dinther	grass	1	1	und.	und.
103	veghel	grass	16	1	0.30	107
108	biest	arable	57	1	0.99	346
109	tilburg	built-up	50	1	0.36	125
110	spoordonk	grass	1	1	und.	und.
111	olland	grass	1	1	und.	und.

Notes 1. The sampling date may vary from 1982-1984; the date indicated prevails in the area concerned.
2. Undetermined values and tritium levels of 1 TU often represent cases with upward seepage.

Table 6.43. Tritium observations for LMG wells in the southern Central Valley (Kempen) (1-83=upper screen,1983; 3-83=lower screen, 1983)

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m{\cdot}a^{-1}$	I_{avg} $mm{\cdot}a^{-1}$
112	son	grass	54	1	0.87	305
113	bladel	arable	55	53	0.41	144
113	bladel	arable	62	55	0.41	144
114	vessem	forest	41	38	0.76	266
115	lieshout	grass	und.	und.	und.	und.
117	helmond	built-up	40	1	0.38	133
118	eindhoven	built-up	96	1	0.44	154
119	aalst	forest	39	1	0.58	205
120	mierlo	forest	83	27	0.85	296
123	vlierden	forest	81	1	0.74	258
124	weebosch	arable	72	80	0.93	324
125	westerh.	arable	78	29	0.71	249
126	leende	forest	88	1	0.60	209
127	budel	built-up	67	18	0.93	325
128	someren	unspec.	und.	und.	und.	und.
129	b.schoot	forest	124	1	0.63	221

Values of recharge, which are less than expected, again indicate the presence of surficial runoff components, diminishing the recharge of deeper groundwater.

6.5.7.4. Northern Peel region

Up to this century, the Peel area was a desolated piece of land, covered by vast heathlands. In winter periods, the land was covered by water but also during summer periods, smaller bogs were present. Only on the fringes of the region did a number of villages develop; here, farmers lived, using the Peel lands for grazing their animals. A large-scale reclamation was only initiated by the central government in the 1930s. At present, almost all of the region is covered by permanent pasture or arable land and some pine forests. In the centre of the area, where the transport capacity for groundwater flow was low, an important raised bog had developed. The peat was exploited up to some 50 years ago. Nowadays the remainder of the Peel is a nature reserve, where peat growth is again being stimulated.

The Peel subsurface consists of relatively coarse sand layers, yet of a limited thickness. Especially where the aquifer is subdivided by clayey layers, deposited during the Tegelen Formation, did peat bogs originate. The base of the aquifer system consists of Tertiary clay layers at a depth of 100 m in the north, but at a much more shallow depth in the southern part. For the interpretation of the tritium data for LMG wells (*Table 6.44*), D=50 m is taken, but the depth may vary widely. Average values for groundwater recharge are:

grassland :	n=3;	$I/p_{avg.}$=0.83 $m{\cdot}a^{-1}$;	$I_{avg.}$=290 $mm{\cdot}a^{-1}$;
arable land:	n=1;	$I/p_{avg.}$=0.87 $m{\cdot}a^{-1}$;	$I_{avg.}$=304 $mm{\cdot}a^{-1}$;
forest areas:	n=3;	$I/p_{avg.}$=1.07 $m{\cdot}a^{-1}$;	$I_{avg.}$=373 $mm{\cdot}a^{-1}$;

6.5.7.5. North Limburg

The river Meuse flows through the north Limburg region in a minor depression, within a generally uplifted area. The east bank has been rising in the geologically recent past, resulting in old river deposits, which are situated above the present river level. In fact, the oldest deposits are found at the highest level. Deposits of minerals, belonging to Lower Pleistocene formations (clay and sand) have been commercially exploited up to now. The land is used for a traditional type of agriculture, but intensive animal husbandry is also strongly developing. Much of the land is planted with forests, which often are of a mixed type. The subsurface has variable features due to a complicated geological situation. For the interpretation of the tritium data for LMG wells (*Table 6.45*), D=50 m is taken, although the depth of the base of the aquifer system may vary widely. Average results for the groundwater recharge, are:

grassland :	n=2;	$I/p_{avg.}$=0.78 $m{\cdot}a^{-1}$;	$I_{avg.}$=271 $mm{\cdot}a^{-1}$;
arable land:	n=3;	$I/p_{avg.}$=0.93 $m{\cdot}a^{-1}$;	$I_{avg.}$=325 $mm{\cdot}a^{-1}$;
forest areas:	n=1;	$I/p_{avg.}$=0.81 $m{\cdot}a^{-1}$;	$I_{avg.}$=284 $mm{\cdot}a^{-1}$;

Table 6.44. Tritium observations from the LMG wells in the northern zone of the Peel area (1-83=upper screen, 1983; 3-83=lower screen, 1983)

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m{\cdot}a^{-1}$	I_{avg} $mm{\cdot}a^{-1}$
100	macharen	grass	57	1	0.93	324
101	schaik	forest	68	39	1.03	360
115	lieshout	grass	1	1	und.	und.
104	odiliap.	forest	62	12	1.08	378
105	beers	grass	43	1	0.31	109
106	landhorst	arable	65	33	0.82	288
107	sambeek	arable	66	18	0.96	337
116	gemert	grass	47	41	1.24	435
121	rips	forest	76	54	1.09	381
122	overloon	arable	76	42	0.82	286

Notes 1. The sampling date may vary from 1982-1984; the indicated date prevails in the area concerned.
2. Undetermined values and tritium levels of 1 TU often represent cases with upward seepage.

6.5.7.6. Central Limburg

The landscape of central Limburg shows much variation. The northern part belongs to the Peel region, which has only been reclaimed relatively recently. An intensive animal husbandry has developed in that area. The Griendtsveen nature reserve forms the boundary between the provinces of North Brabant and Limburg. The west part of the region is situated in the Central Valley; it has a sandy soil. A number of villages in that area were traditional agricultural centres, but it was also where many industrial activities originated in this past century. Intensive animal husbandry is at present an important economic activity. On the east bank of the River Meuse, mixed agriculture, including specific forms of horticulture (asparagus), has been practised for a long time. However, also at many farms on the east bank of the Meuse, land use has turned into intensive animal husbandry. Some of the old river terrasses contain much-valued nature reserves.

Due to a variable structure of the soil caused by its geological situation, the geohydrological situation is also variable. Although the aquifer systems at the Central Valley occupy large zones in the subsurface, the presence of clay layers may reduce the thickness of the upper aquifer. In the geologically uplifted areas, the base of the full aquifer system is at a relatively shallow depth. The interpretation of the tritium data from the LMG wells (*Table 6.46*) has been based on D=50 m as a first approach. Average results for the groundwater recharge, are:

grassland :	n=2;	undetermined	
arable land:	n=4;	$I/p_{avg.}$=0.95 $m{\cdot}a^{-1}$;	$I_{avg.}$=333 $mm{\cdot}a^{-1}$;
forest areas:	n=2;	$I/p_{avg.}$=0.81 $m{\cdot}a^{-1}$;	$I_{avg.}$=286 $mm{\cdot}a^{-1}$;

6.5.8. Summary of results

Based on tritium data, the downward percolation at the locations of the detailed investigations on the test

Table 6.45. Tritium levels of the LMG wells in north Limburg (1982-84) and an interpretation

LMG	Location	Land use	1-84 TU	3-84 TU	3-82 TU	$I/p_{avg.}$ $m{\cdot}a^{-1}$	$I_{avg.}$ $mm{\cdot}a^{-1}$
245	milsbeek	grass	45	48	48	0.90	315
246	heijen	arable	38	51	58	0.92	323
247	well	arable	67	36	31	1.05	368
248	castenray	forest	75	22	14	0.81	284
250	grubbenvorst	arable	70	39	31	0.81	284
251	arcen	grass	58	1	1	0.65	228

Table 6.46. Tritium levels of the LMG wells in middle Limburg (1982-84) and an interpretation

LMG	Location	Land use	1-84 TU	3-84 TU	3-82 TU	$I/p_{avg.}$ m·a^{-1}	$I_{avg.}$ mm·a^{-1}
252	weert	built-up	1	41	16	0.99	348
253	nederw.	arable	52	42	34	1.12	391
254	echel	grass	1	1	1	und.	und.
255	reuver	grass	46	1	1	und.	und.
256	baexem	arable	38	1	1	0.79	277
257	roermond	unknown	41	1	1	0.36	125
258	herkenb.	forest	60	15	17	0.89	313
259	peij	arable	33	7	1	0.83	289
260	nieuwstad	forest	20	6	7	0.74	258
261	roosteren	unknown	110	1	6	0.61	213
271	sevenum	arable	81	9	7	0.96	338

farms and near the LMG wells has been estimated. The values represent long-term averages, and a long-term average of the groundwater recharge (I) can be derived. The computed average recharge can be compared to the value of precipitation (P) minus the potential evapotranspiration (E_p) for the various vegetation types. For forested areas it is assumed that $E_p=E_o$. An elaboration for the determined values of I in the various subregions yields the following values for the difference:

North-west Babant:

Bavel test farm; grassland:	$P-E_p-I= 800-560-155=+85$ mm·a^{-1};
LMG wells; grassland:	$P-E_p-I= 800-565-270=-35$ mm·a^{-1};
LMG wells; arable:	$P-E_p-I= 800-510-335=-45$ mm·a^{-1};
LMG wells; forest areas:	$P-E_o-I= 800-705-280=-185$ mm·a^{-1};
Central Valley, north; Meierij van Den Bosch:	
Moerg. test farm; grassland:	$P-E_p-I= 800-555-320=-75$ mm·a^{-1};
Best test location; maize/grass:	$P-E_p-I= 750-560-100=+95$ mm·a^{-1};
LMG wells; grassland:	$P-E_p-I= 750-560-310=-120$ mm·a^{-1};
LMG wells; arable:	$P-E_p-I= 750-495-345=-90$ mm·a^{-1};
Central Valley, south; Kempen:	
LMG wells; grassland:	$P-E_p-I= 750-560-305=-115$ mm·a^{-1};
LMG wells; arable land:	$P-E_p-I= 750-505-285=-40$ mm·a^{-1};
LMG wells; forest areas:	$P-E_o-I= 750-700-240=-190$ mm·a^{-1};
Peel region, north:	
Venhorst test location; maize:	$P-E_p-I= 740-500-290=-50$ mm·a^{-1};
LMG wells; grassland:	$P-E_p-I= 740-555-290=-105$ mm·a^{-1};
LMG wells; arable land:	$P-E_p-I= 740-500-305=-65$ mm·a^{-1};
LMG wells; forest areas:	$P-E_o-I= 740-690-370=-320$ mm·a^{-1};
North Limburg:	
Wanroij test farm; grassland:	$P-E_p-I= 750-550-310=-110$ mm·a^{-1};
LMG wells; grassland:	$P-E_p-I= 755-555-270=-70$ mm·a^{-1};
LMG wells; arable land:	$P-E_p-I= 755-500-325=-70$ mm·a^{-1};
LMG wells; forest areas:	$P-E_o-I= 755-690-285=-220$ mm·a^{-1};
Middle Limburg:	
Sevenum test farm; grassland:	$P-E_p-I= 740-555-360=-175$ mm·a^{-1};
LMG wells; grassland:	undetermined
LMG wells; arable land:	$P-E_p-I= 740-500-335=-95$ mm·a^{-1};
LMG wells; forest areas:	$P-E_o-I= 740-695-260=-215$ mm·a^{-1};

The conclusions from the above review are:

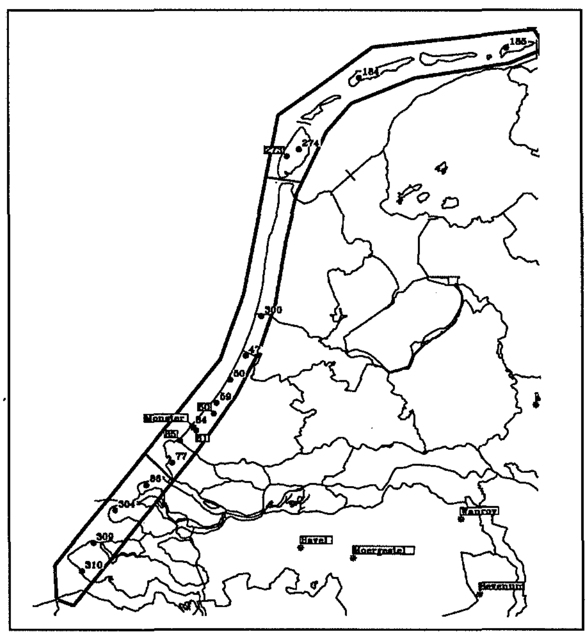
1. The difference between potential and actual groundwater recharge for agricultural lands often takes a negative value, indicating that the sum of the evapotranspiration deficit and the applied sprinkling water has the order of magnitude of 70 mm·a^{-1}, or more. The wide range of values may be caused by inaccuracies in the tritium interpretation.
2. The difference has high values in forested areas, indicating that the estimate, by assuming that $E_p=E_o$, does not yield realistic results. The number of forest locations is small in each region, which contributes to the inaccuracy of the results. Another reason to suspect the interpretation of tritium data, is the location of the wells near open spaces.
3. Areas with an important surficial discharge are present.

6.6. The coastal dunes

6.6.1. Situation and hydrogeology

Dunes are present from the extreme south-west part of the country to the island of Rottumeroog in the north-east (*Fig.6.178*), but not as a continuous ridge. In the north, the dunes constitute oblong islands with tidal inlets in between. In the south-west, large estuaries have broken the ridge, such that isolated dune areas remained on the seafront of clayey islands. Only in the provinces of North and South Holland, are t he dunes still present in the form of a long and uninterrupted coastal ridge. The width of the dune area stretches form some hundreds of metres to several kilometres. The tops are mostly 10 to 20 m above sea level, but the highest top (Schoorl) reaches 60 m. The actual dune ridge originated less than 1000 years ago, replacing an older system of coastal barriers. The old system can locally still be recognized as a slightly elevated region with sandy soils. Originally, the dune ridges had a vegetation, consisting, in some places, of deciduous forest, but elsewhere of open windblown plains. These forests were cleared starting as early as more than 1000 years ago. The actual natural dune vegetation is a mixture of grasses, mosses and shrubs (dune buckthorn). In this century, large parts of the dune ridge have been planted with pine forests. The dunes remained wastelands for a long time, up to 100 years ago, when public waterworks in the western Netherlands started to abstract fresh groundwater. Locally, the fresh groundwater in the dune area became overexploited. At present, the dune region contains large areas where the groundwater is artificially recharged by river water. The coastal dunes form an area with great natural and recreational value.

Fig.6.178. LMG wells in the coastal dunes.



The subsurface of the dunes contains sandy layers to a depth of mostly more than 100 m, except in the south-west and in the north-east parts. However, the deepest zones of the aquifer system contain brackish groundwater. As early as 1888, Badon Ghijben developed his theory of a freshwater lens in the dune subsurface, which floats on virtually stagnant salt water. Within the sandy subsurface of the dune ridges, a freshwater lens with a variable thickness of a few dozen metres, depending on the local hydrological situation, has originated. The exploitation by public waterworks of less than 100 years caused a local upconing of deeper salt groundwater, thus limiting a further groundwater extraction.

In the old situation, the dune area consisted of an alternation of dry dunes and wet valleys. Many of the valleys even contained shallow ponds, at least in the winter period. Surface water courses could not develop due to the dune configuration; the excess water had to be discharged by evaporation and groundwater flow. The planting of pine forests and the water abstraction have caused a predominantly dry situation. Wet dune valleys are rare at present, but highly valued from an ecological point of view. For the interpretation of tritium data from fresh groundwater, it is assumed that the depth of the fresh lens constitutes the base of the flow system, with only the lens being available for flow.

6.6.2. Eight tritium profiles in groundwater of the coastal dunes near Monster

6.6.2.1. Location and set-up of the investigations

The situation of the investigated site at the village of Monster is determined by its location near the mouth of large rivers. The Roman Helinium, being the estuary of Meuse and Rhine branches, was located close to the area of investigation. In the Middle Ages, the region was subject to an inundation by the sea, depositing the clayey and loamy Westland soil. The coastal dunes to the south of The Hague still consist of a narrow zone of low dunes. The dune area at Monster (*Fig.6.179*) has a width of approximately 400 m and a height, which varies between 6 and 12 m above m.s.l.. Just north of Monster, the dune area widens and a zone of former beach deposits is

Fig.6.179. Situation and location of the wells.

present. At the transition, a well field was installed, delivering artificially recharged dune water to a number of villages in the area. The pumped volume of groundwater amounted to about $4*10^6$ $m^3 \cdot a^{-1}$ between 1975 and 1980. In the same period the dune area received an appoximâtely equal artificial recharge. The dunes south of the well field compose a nature reserve inaccessible to the public. The vegetation consists of mosses and shrubs (dune buckthorn). The dune area to the north is more open to external influences; a large camping site is present and other human activities take place. The northern wells are situated in an open space with a degradated dune vegetation. The inland area covered by greenhouses is called the Westland; it is largely used for horticulture.

Near the well field, detailed geohydrological investigations were executed at the end of the 1970s (Duijvenbooden, Gast and Taat 1985). To the north of the well field, the observation wells 149, 150 and 151 were drilled and provided with mini-screens to assess the effect of a nearby landfill. The mini-screens were attached at intervals of 1 m to the rising pipes of screens, reaching depths between 20 and 25 m below land surface. At the south side of the well field, another set of observation wells (152, 175 and 177) was installed to a depth of some 20 m, these wells were also provided with mini-screens. The aim of the latter investigations was to collect information for setting up the national groundwater monitoring network.

The samples taken from the available mini-screens were analyzed with regard to conventional chemical parameters in groundwater. At the same time, the levels of the natural isotopes ^{18}O and ^{3}H were determined by the Centre for Isotope Research of Groningen University (CIO). A set of isotope values containing more than 100 tritium determinations is available for the study area in the form of eight detailed tritium profiles, in combination with additional information. Especially the tritium data set is interesting:

1. The observations represent a very detailed sampling.
2. One series of observations was repeated three times.
3. Characterized by high tritium levels in rainfall, the age of the samples could also be expected to fall, at least partly, in the period 1962-1965,

6.6.2.2. The hydrogeological situation

An overview of the geological formations present in the area is given by RGD (1975), by ICW (1975) and by DGV-TNO (1980). The structure of the layers, including the groundwater flow, has been summarized in *Fig.6.180.* The subsurface contains mainly sandy sediments down to a depth of 120 m, where the top of the clay layers of the Maassluis Formation is situated. Two subaquifers can be distinguished. The deep aquifer of older Pleistocene layers has its top at a

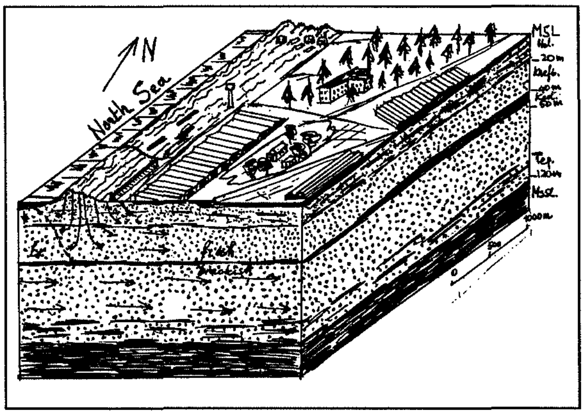


Fig.6.180. Structure of the subsurface of the well field.

depth of roughly m.s.l.-50m, where clay layers of the Kedichem Formation constitute a resisting layer. Above m.s.l.-50m, an upper aquifer is present. The Holocene sediments in the area have developed into sandy layers, as became clear from soil samples; only at their base, at a depth of about m.s.l.-20m, are thin clay layers present. The Holocene sediments form part of the upper unconfined aquifer.

Generally, the fresh/brackish interface is located within the Kedichem clay layers (ICW, 1976). However, in the deeper screens of the wells 150 and 151, which are near the beach, groundwater with an increased salt level (*Table 6.47*) was already observed at a depth of less than 20 m. The other, more inland, wells indicated completely fresh groundwater. For the interpretation of the tritium profiles, it may be assumed that the upper aquifer behaves as a single unconfined aquifer, with its base at a depth of D=50 m. At least in the upper zone, a fresh groundwater flow will be present.

A water divide was observed in the dune area: the groundwater flows both to the coast and land inward. As no surface water is present, the groundwater recharge will be equal to the local rainfall excess. The average local rainfall is near 800 $mm \cdot a^{-1}$. The location at Monster is covered by a natural dune vegetation, consisting of mosses and dune shrubs for which the average actual evapotranspiration is estimated (Stuyfzand, 1993) at roughly 480 $mm \cdot a^{-1}$ and, hence, the average annual rainfall excess is 320 $mm \cdot a^{-1}$. The groundwater heads in the middle of the dune strip are about m.s.l.+2.5 m. Additionally, a brackish groundwater flow from sea to land will exist in the deep subaquifer because inland polder levels are below m.s.l.

A notable feature is formed by some relatively high values of the ^{18}O level in the groundwater (*Table 6.47*). The average ^{18}O level in the rainfall of the Netherlands is $[^{18}O]= -7.5‰$ (SMOW), which was also often found in groundwater throughout the country (Mook, 1989). The observed deviations may have various reasons. An extra inflow of sea water with high ^{18}O levels seems less likely, because that would also have a pronounced effect on chloride levels. Also, the surficial discharge of part of the rainfall may be excluded, no visible drainage means being present. However, the open water evaporation of rainfall intercepted by the vegetation, or from the land surface, may also result in an increase of heavy isotopes, including tritium. The latter cause will prevail in the Monster situation.

6.6.2.3. *Interpretation of the tritium profiles*

The presence of groundwater recharge becomes clear from the tritium profiles in well 152 (*Figs.6.181; 6.182; 6.183*); the measurements were repeated dur-

Table 6.47. Summary of some observations in the wells with mini-screens

		152-77	152-78	152-79	149-78
Cl^- ($mg \cdot l^{-1}$)	avg.			203	179
(1980-07)	range			59-320	38-223
^{18}O (‰SMOW)	avg.	-6.29	-7.22	-7.02	-5.04
date as ^3H	range	-5.7/-6.9	-7.4/-6.8	-6.6/-7.7	-4.6/-6.9
		150-78	151-78	175-79	177-79
Cl^- ($mg \cdot l^{-1}$)	avg.	891	563	159	171
(1980-07)	range	92-2680	96-1590	70-216	80-257
^{18}O (‰SMOW)	avg.	-6.99	-6.98	-7.35	-7.33
date as ^3H	range	-6.5/-7.5	-6.5/-7.6	-7.2/-7.7	-7.2/-7.5

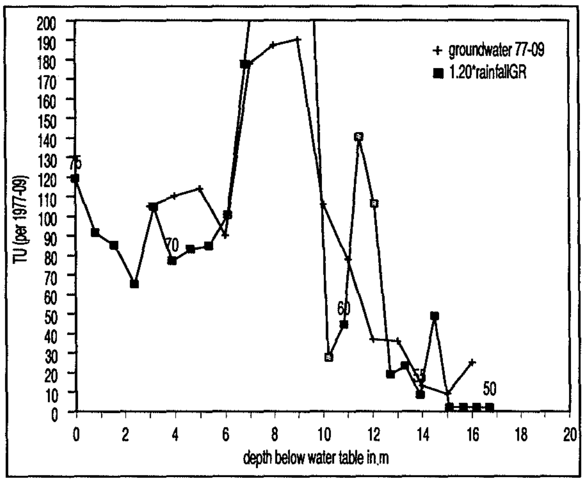


Fig.6.181. ^3H data well Mo-152 in 1977.

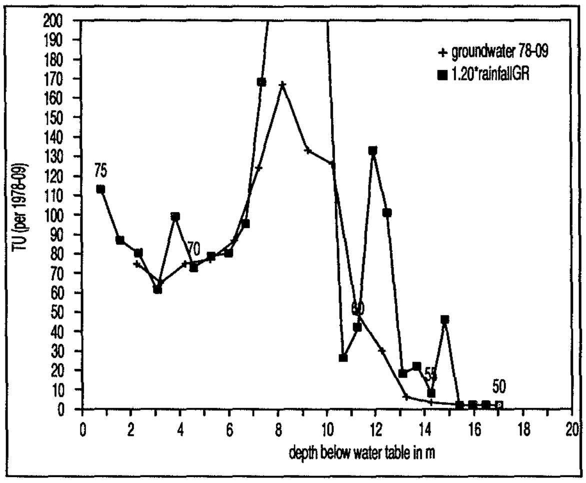


Fig.6.182. ^3H data well Mo-152 in 1978.

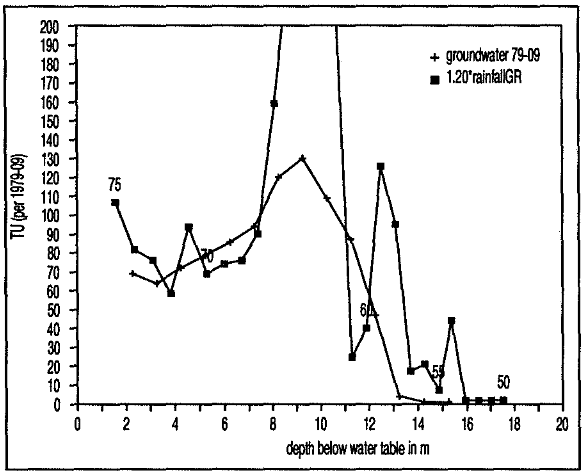


Fig.6.183. ^3H data well Mo-152 in 1979.

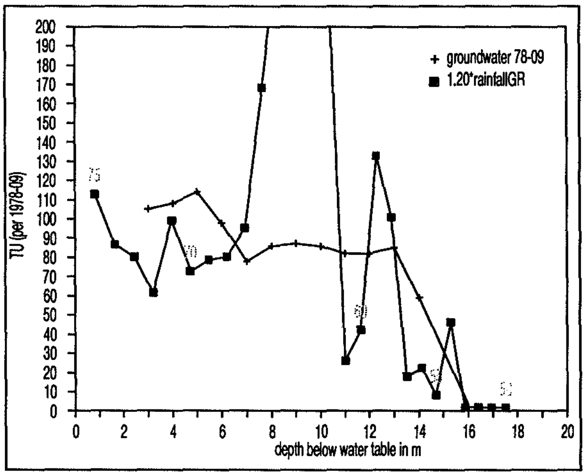


Fig.6.184. ^3H data well Mo-149 in 1978.

Table 6.48. Summary of the interpretation of the tritium data

Well		152-77	152-78	152-79	149-78
D_{lay}	m	50	50	50	50
reg.fact.	f (-)	1.20	1.20	1.20	1.20
I/p	$m \cdot a^{-1}$	0.814	0.800	0.800	0.829
I(p=0.35)	$mm \cdot a^{-1}$	285	280	280	290
gr.w-ls	m	-2.5	-2.25	-2.25	-3.0
Well		**150-78**	**151-78**	**175-79**	**177-79**
D_{layer}	m	50	50	50	50
reg.fact.	f (-)	1.10	1.10	1.05	1.05
I/p	$m \cdot a^{-1}$	0.800	0.786	0.786	0.786
I(p=0.35)	$mm \cdot a^{-1}$	280	275	275	275
gr.w-ls	m	-2.5	-2.25	-2.25	-2.50

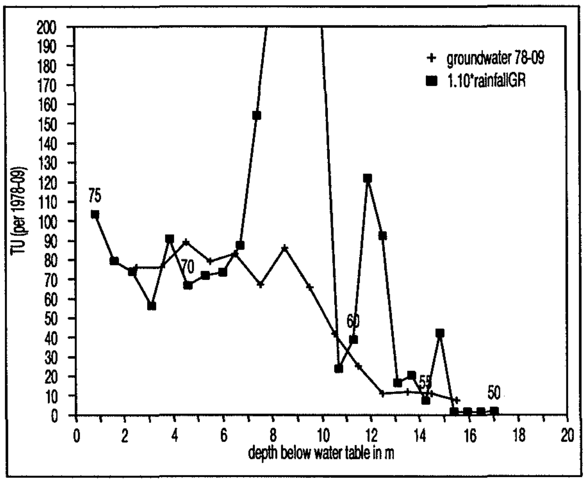


Fig.6.185. ^3H data well Mo-150 in 1978.

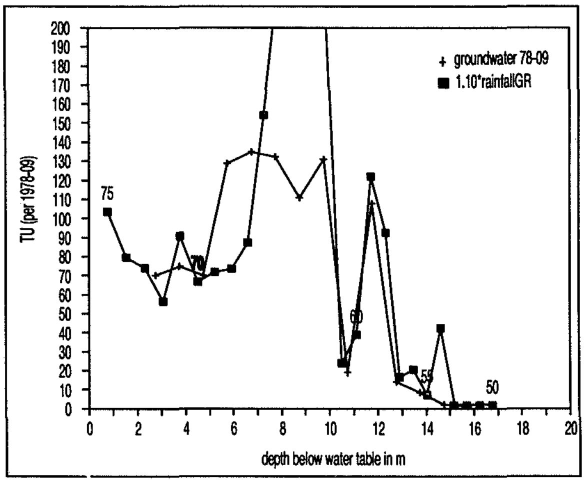


Fig.6.186. ^3H data well Mo-151 in 1978.

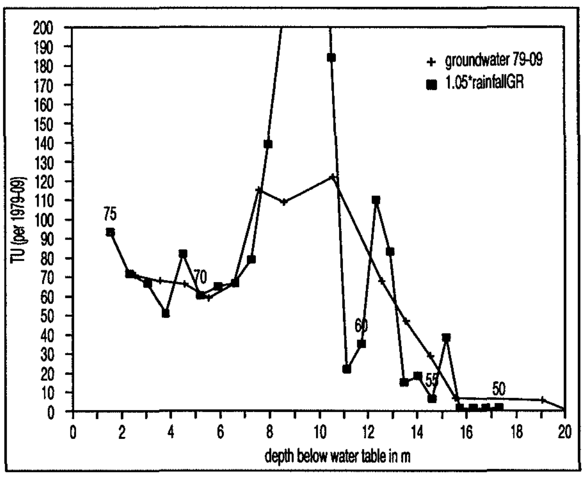


Fig.6.187. ^3H data well Mo-175 in 1979.

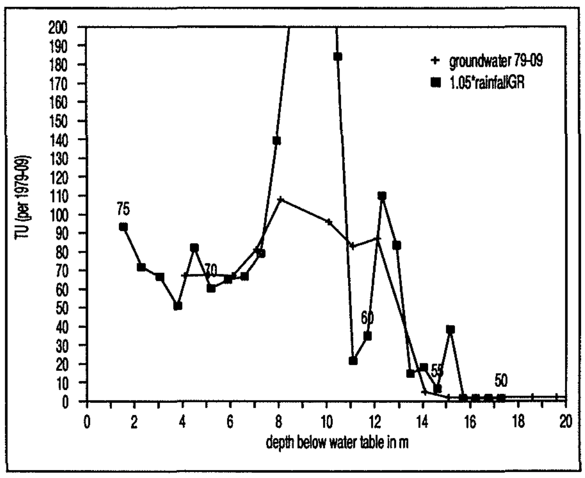


Fig.6.188. ^3H data well Mo-177 in 1979.

ing the course of three years. Apart from the observations at well 152, detailed tritium observations are available for five other wells, sampled in 1978 and 1979 (*Figs.6.184-188*). In all eight cases, detailed tritium profiles can be composed. These indicate the variations in tritium level of groundwater versus depth and can be interpreted in the sense of groundwater travel times since the time of recharge. At the interpretation it was assumed that the travel time in the unsaturated zone had been two years, which is a reasonable estimate, given the depth of the water table (*Table 6.48*). Additionally, the reference series of the ^3H level in rainfall in Groningen is multiplied by a factor f, which in any case represents a regional effect, but which may also represent other possible changes, for example,by enrichment. The interpretation is based on a depth D=50 m of the aquifer. It leads to a determination of values for f and I/p. By assuming that the porosity is p=0.35, values for the groundwater recharge can also be determined.

The results of the interpretation are represented in *Figs.6.181* to *6.188* and summarized in *Table 6.48*. A general observation is, in the first place, that a satisfactory matching of both curves can be reached in most cases. A less perfect match, as observed in *Figs.6.184* and 185, may be ascribed to disturbance factors, like human errors in sampling, transport, storage, analysis and reporting of the tritium level; a wrong schematisation of the situation, or unknown factors may also cause a less perfect match.

Furthermore, the interpretation results in values of groundwater recharge, which vary within a narrow range and where I=280 mm·a^{-1} (at p=0.35) as a mean value. The interpreted value of f varyies between f=1.05 and f=1.20, which is equal to the expected value, or slightly higher, in rainwater (f=1.05). Hence, also the interpretation of the tritium data indicates, in some cases, a (modest) enrichment, which most prob-

Table 6.49. Tritium data from the LMG wells in the West Frisian Islands (1-83= upper screen, 1983; 3-83=lower screen,1983)

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m{\cdot}a^{-1}$	I_{avg} $mm{\cdot}a^{-1}$
184	w.tersch.	forest	33	6	0.96	335
185	schierm.	dune	57	83	0.81	284
273	de koog	unspec.	9	1	und.	und.
274	de waal	arable	1	1	und.	und.

ably was caused by an effect of open water evaporation, as already suggested by the observed ^{18}O values.

A notable coincidence is that the least perfect match, with regard to well 149-78 (*Fig.6.183*), also concerns the well which shows a deviating groundwater composition in other respects (^{18}O levels, chemical composition). The well is located in a place where the danger of external disturbances is great. A possible explanation of the deviating behaviour has been omitted, as it would require too much data not known.

When considering the two curves used per case to illustrate the comparison between ^3H levels in rainfall in time and the ^3H levels in groundwater versus depth, it appears that a fully perfect fit is never reached, including all the observed levels in groundwater. Especially the groundwater, which was presumably recharged in 1962-1965, did not carry the expected tritium content of rainfall to its full extent.

6.6.2.4. General aspects of the Monster investigations

Deviations between the estimated tritium levels in rainfall and measured groundwater levels, as observed in the Monster case, will be caused by a variety of errors and imperfect schematisations, which can probably never be fully traced. That situation also implies that a fully mechanical curve-fitting will be accompanied by considerable methodological difficulties. A visual matching of the two curves, taking into account all available hydrological evidence, is preferable (like it was applied).

The results of the interpretation, represented in *Table 6.48,* show a large similarity with regard to the groundwater recharge. It had to be expected that the comparable types of vegetation in themselves would result in similar values of groundwater recharge. The calculated average velocity of $I/p=0.80$ $m{\cdot}a^{-1}$, is probably a representative value for a normal dune area in the climatological situation valid at Monster. The lysimeter data given by Stuyfzand (1993) and, notably, the value for the rainfall excess of $I=320$ $mm{\cdot}a^{-1}$ in a situation with a natural dune vegetation (Castricum-2), only correspond to the Monster results if a relatively high value of $p=0.40$ is assumed (like Stuijfzand indeed does). A slightly higher value for the porosity of the recently deposited dune sands of $p=0.40$ is, if compared to the older inland sand layers, not unlikely.

The regional deviation of the tritium levels in the rainfall at Monster is, if compared to Groningen rainfall, estimated at $f=1.05$ (Chapter 4). The observed tritium levels in groundwater indicate values which are either equal to $f=1.05$, or slightly larger. The consideration of the ^{18}O levels, observed in the groundwater at Monster, also leads to the conclusion that the heavy isotopes in dune groundwater may have become slightly enriched by open water evaporation. In considering *Tables 6.47* and *6.48*, it follows that the wells, indicating enriched ^{18}O levels in groundwater, if compared to local rainfall, are the same wells where the factor f assumes the largest values. The occurrence of an open water evaporation preceding groundwater recharge corresponds to the observation (Stuyfzand, 1993) that the excess rainfall is predominantly infiltrating in the soil of dune valleys after surface flow along dune slopes covered by a natural dune vegetation.

In addition to incidental deviations between measured and expected ^3H levels in groundwater, it seems that there is a systematic error with regard to the high values in rainfall, as observed in the years 1962-1965. The ^3H levels observed in Monster groundwater, estimatedly recharged in 1962-1965, are systematically lower than would be expected on the basis of rainfall ^3H levels in those years. Groundwater, originating in the period 1962-1965, carries roughly 50% of the expected tritium levels in rainwater. The explanation could be that the Vienna figures from those years cannot be extrapolated in a simple way to the Netherlands situation.

6.6.3. Tritium data of Groundwater Monitoring Stations

6.6.3.1 West Frisian Islands (Waddeneilanden)

Generally, the West Frisian Islands consist of dune ridges and some low land separated from the Netherlands mainland by the shallow Wadden Sea. The dune ridges protect the islands from the North Sea; some coastal accretion has initiated clayey soils on the land side, which are now used for a modest agriculture. The West Frisian Islands have a great recreational value, with parts being highly valued nature reserves.

The fresh groundwater lens is recharged by the local rainfall excess and it is heavily exploited to sustain the public water supply of the islands, also by providing drinking water to the great mass of tourists visiting the islands in summer periods. For the interpretation of tritium data, D=60 m is assumed, although the actual situation may deviate. The results, shown in *Table 6.49*, are:

dune vegetation:	n=1;	I/p=0.81 $m \cdot a^{-1}$;	I=284 $mm \cdot a^{-1}$ (p=0.35);
forest:	n=1;	I/p=0.96 $m \cdot a^{-1}$;	I=335 $mm \cdot a^{-1}$ (p=0.35).

6.6.3.2. Holland coastal dunes

Part of the sea defence in the north of North Holland from Den Helder to Petten consists of a dike. However, from Bergen to The Hague, high dunes occupy a broad strip. In many places, an adjacent zone of former old dunes, also with a sandy soil, was levelled down, especially to make bulb-growing possible. For more than 100 years, the dune area in the west of Holland has been intensively used by public water-supply companies for waterworks nowadays based on artificial recharge. The coastal dunes consist of areas with a great natural and recreational value.

Corresponding to the width of the dune zone, the fresh groundwater lens originally also had a considerable depth in the Holland dunes. However, the abstraction of dune water for public water supply caused the salt/fresh interface to rise. For the interpretation of tritium data from LMG wells, D=80 m is assumed. Average results as shown in *Table 6.50* are:

dune vegetation:	n=3;	I/p=0.97 $m \cdot a^{-1}$;	I=340 $mm \cdot a^{-1}$;
garden:	n=2;	I/p=0.93 $m \cdot a^{-1}$;	I=325 $mm \cdot a^{-1}$.

6.6.3.3. Zeeland dunes

The Zeeland dunes consist of relatively small dune areas at the side facing the North Sea. Due to low population densities of the adjacent regions, the dune areas were only modestly used for groundwater abstraction. Only in recent years, were some artificial recharge works installed. The Zeeland dunes have a great natural and recreational value. For the interpretation of tritium data, D=50 m is assumed, but in the actual situation, the depths may deviate. Average results, as shown in *Table 6.51*, are:

dune vegetation:	n=2;	I/p=0.49 $m \cdot a^{-1}$;	I=170 $mm \cdot a^{-1}$;
grassland:	n=1;	I/p=0.53 $m \cdot a^{-1}$;	I=185 $mm \cdot a^{-1}$;
arable land:	n=1;	I/p=0.92 $m \cdot a^{-1}$;	I=320 $mm \cdot a^{-1}$.

Table 6.50. Tritium data from the LMG wells in the Holland coastal dunes (1-83= upper screen, 1983; 3-83= lower screen, 1983)

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m \cdot a^{-1}$	I_{avg} $mm \cdot a^{-1}$
300	ijmuiden	built-up	39	i	0.77	268
47	haasveld	dune	56	63	1.01	352
48	hillegom	garden	58	1	0.65	228
50	katwijk	garden	47	1	1.21	425
303	noordwijk	arable	58	82	1.00	350
59	wassenaar	dune	31	129	1.14	401
60	den haag	built-up	98	1	0.60	209
77	rockanje	forest	7	1	und.	und.
84	monster	dune	74	1	0.77	268
85	h.vanholl	dune	26	1	und.	und.

Table 6.51. Tritium data from the LMG wells in the Zeeland coastal dunes (1-83= upper screen, 1983; 3-83=lower screen, 1983)

LMG no.	Location	Land use	1-83 TU	3-83 TU	I/p_{avg} $m{\cdot}a^{-1}$	I_{avg} $mm{\cdot}a^{-1}$
86	ouddorp	arable	49	1	0.92	320
304	haamstede	grass	76	1	0.53	186
309	vrouwenp.	dune	75	1	0.65	226
310	biggek.	dune	74	1	0.33	116

6.6.4. Summary of results

The results derived from the interpretation of groundwater recharge in the coastal dunes can be compared to average values of rainfall minus the potential evaporation for the various vegetation types. For agricultural areas, the potential evapotranspiration can be estimated by using appropriate vegetation factors. For natural vegetations, the calculated average actual evapotranspiration can be related to the Penman open water evaporation.

An elaboration of results obtained for the various subregions yields:

West Frisian Islands and Holland dunes:		
	P=780-820 $mm{\cdot}a^{-1}$	E_r=600 $mm{\cdot}a^{-1}$;
	E_{arable}=540 $mm{\cdot}a^{-1}$;	E_o=750 $mm{\cdot}a^{-1}$;
Monster location (dune veg.):	I=280 $mm{\cdot}a^{-1}$;	E_a=520 $mm{\cdot}a^{-1}$;
LMG wells (dune vegetation):	I=325 $mm{\cdot}a^{-1}$;	E_a=475 $mm{\cdot}a^{-1}$;
LMG wells (garden cultiv.):	I=325 $mm{\cdot}a^{-1}$;	E_a=475 $mm{\cdot}a^{-1}$;
Zeeland dunes:	P=730 $mm{\cdot}a^{-1}$;	E_r=600 $mm{\cdot}a^{-1}$;
LMG wells (dune vegetation):	I=170 $mm{\cdot}a^{-1}$;	E_a=560 $mm{\cdot}a^{-1}$;
LMG wells (grassland):	I=185 $mm{\cdot}a^{-1}$;	E_a=545 $mm{\cdot}a^{-1}$;
LMG wells (arable land):	I=320 $mm{\cdot}a^{-1}$;	E_a=410 $mm{\cdot}a^{-1}$;

The conclusion of an elaboration of results for agricultural areas is that the actual evapotranspiration is smaller than the potential evapotranspiration. The differences have the same order of magnitude as for the other sand regions. However, the number of observations is too small to draw strict conclusions. The average actual evapotranspiration in a dune area with a natural vegetation is in the order of E_a=500 $mm{\cdot}a^{-1}$ and, hence, by approximation E_a/E_o=0.7. The range of values is large in the case of dune vegetations, which is partly due to a great variability of the different vegetations in dune areas. But also the detailed hydrological situation may play a role. A general conclusion is that the interpretation of tritium levels in the groundwater of areas with a natural vegetation always necessitates a proper assessment of the local vegetation and the local hydrological situation.

A factor to be taken into account in the interpretation of tritium data is the possible systematic deviation of groundwater levels from the values in local rainfall, which is caused by an effect of open water evaporation. Apart from a regional factor indicating differences in the tritium level of Groningen precipitation and of local rainfall, the groundwater in the dunes is influenced by an effect of open water evaporation, which leads to a modest (0% to 20%) enrichment in tritium levels.

In the interpretation of groundwater recharged in the period 1962-1965 attention should be given to possible deviations of the groundwater tritium levels from the estimated tritium levels in rainfall. One conclusion, most probably of a general character, is that the absolute values of the large tritium levels observed in Vienna rainfall during the years 1962-1965 cannot be traced back in the groundwater. The rainwater values of the Netherlands were probably 50% lower than those corresponding to the Vienna figures during those years.

7. EVALUATION AND GENERALISATION OF RESULTS; MAPPING OF TRAVEL TIMES

7.1. Evaluation of the basic assumptions

7.1.1. Tritium in rainfall; regional trends

A major method used for groundwater dating is the comparison of rainfall and groundwater tritium levels. Interpretation requires knowledge of tritium levels in the precipitation, recharging the sampled groundwater. The reference series used consisted of annual averages of the tritium levels in Groningen rainfall, in combination with regional factors, derived from a comparison with rainfall levels measured during 1980-1986 in twelve other stations. The tritium levels in Groningen rainfall were based on locally measured monthly values after 1970, on a correlation with values measured in Vienna during 1960-1970 and with values measured in Ottawa before 1960. A relevant question is, whether the extrapolated rainfall levels, measured at far-off locations, represent a satisfactory reference series for the local groundwater recharge in the Netherlands. Two periods are distinguished, the first one covering the years before 1970 and the second period the years after 1970. After 1970, the Groningen rainfall tritium levels are an elaboration of local measurements. Moreover, the sources of atmospheric tritium changed after 1970 from remnants of nuclear tests to emissions of local industrial sources.

The rainfall series after 1970 can be well recognized in the interpreted groundwater, implying that the measured rainfall levels after 1970 are confirmed by groundwater observations. Moreover, at ten investigated farms with a grass cover, the multiplication factors corresponded to the independently determined regional factors in rainfall. The same conclusions follow from the Monster and Venhorst observations.

The rainfall tritium levels assumed before 1970 are only present in part of the investigated groundwater. The interpretation leads to the conclusion that the high levels measured in Vienna rainfall during the period 1962-1966, cannot fully be traced back in Netherlands groundwater. The rainfall tritium levels for that period, which were derived from a correlation with Vienna rainfall, will most likely have to be reduced by roughly 50%, to comply with the levels in groundwater recharge. Matching adapted rainfall tritium levels with groundwater levels is presented in Figs. 7.1 to 7.4 (compare *Figs. 5.39; 5.51; 6.40* and *6.182*). The evidence for a reduction is not very convincing, yet, better matching has been reached.

A disturbing factor is that regional factors valid for the period from 1970 to the present are most probably different from the factors for the earlier period. From Weiss et al. (1978), it can be derived that the range of regional factors throughout the Netherlands before 1970 varied from 1.0 at Groningen to 1.12 at Liege. However, the investigated groundwater was mostly recharged after 1970. The conclusion is that the assumed regional relationships are valid in the years after 1970 and that they constitute a satisfactory first approach for data on tritium in rainfall of the Netherlands in the period before 1970.

7.1.2. Geohydrological parameters (effective porosity, shallow mixing)

For the interpretation of the observed groundwater tritium levels, assumptions had to be made concerning the type of groundwater flow. A presupposition already discussed in section 2.2.1, is the mixing on an annual basis of the downward percolating water in the unsaturated zone before groundwater in the saturated zone is recharged. The observed tritium profiles confirm this assumption, especially the profiles composed of values observed in mini-screens. The seasonal fluctuations in tritium levels (*Fig.4.2*) are in the same order of magnitude as the yearly averages. The vertical downward velocity has an order of magnitude of 1 $m{\cdot}a^{-1}$. If seasonal variations were present in the saturated groundwater, they would have appeared in the mini-screen configuration at intervals of half a metre. The fact that a matching with annual averages of rainfall tritium levels results in the great majority of cases in a good fit, implies that seasonal fluctuations are virtually absent in the groundwater of saturated layers.

The interpretation results in values for the velocity of the downward percolation. At the phreatic level, the downward velocity is equal to I/p (downward flux, divided by effective porosity). The downward flux could be determined in other ways at some of the detailed investigations, allowing a comparison with tritium determinations. At the Best investigation, elaborating the measured position of a polluted groundwater plume, in combination with known permeabil-

At increasing depths, the vertical velocity decreases, as it should. For small values of z (z<<D), the equation is reduced to:

$$t=z*p/I, \text{ or } z=t*I/p \qquad \text{(constant vertical percolation)}$$

Hence, at deep aquifers, even a constant vertical velocity might be assumed for the top layers, leading to the same results, if compared to the approach of a decreasing flow towards depth. The roughly 20 observed tritium profiles generally reached depths between 10 and 20 m. The aquifer thickness for each particular case was estimated from geological data and assigned a fixed value for the various geohydrological regions. In cases where the aquifer was thin, like Veendam and Vredepeel, the assumption of decreasing vertical velocities towards depth, yielded satisfactory results, indicating that the regional flow equation represents a good approach. The interpretation of tritium levels will result in different values for I/p if the aquifer depth is changed. In most cases an interpretation was possible and the results obtained represented acceptable values, indicating that, in general, the correct order of magnitude for D was chosen.

Only in the cases of Holten and Griendtsveen, did the observed tritium profiles show discontinuity, which could be readily explained by the respective hydrological situations. In all other cases, the complete tritium profile obeyed a single and consistent flow pattern, occupying the whole Pleistocene aquifer system. Moreover, the same conclusion holds for most observed tritium levels in monitoring wells of the national and provincial networks (with the deepest screen at a depth of 25 m).

Hence, the great majority of the observed wells is found in one coherent groundwater flow pattern, occupying the full Pleistocene aquifer, except in areas where the subsurface contains a relatively thick series of poorly permeable clay layers. The existence of separate (nested) groundwater flow systems, as suggested by Engelen (1989) is not supported by the investigations in the vast areas where tritium data are available. However, the wells considered are mostly located in areas with relatively deep groundwater levels. In stream valleys and seepage zones with shallow groundwater levels, part of the rainfall excess will be discharged by surficial flow components. The areas concerned are relatively small (*Fig.7.5*) and it is also questionable whether or not the surficial flows belong to the groundwater domain. The conclusion is that the development of a system analysis to distinguish separate groundwater flow systems, will be of limited use for the sandy areas of the Netherlands.

7.2. Groundwater recharge in the sandy regions

7.2.1. Extrapolation of recharge, derived from tritium data

The detailed investigations and the regional surveys resulted in conclusions on the magnitude of the groundwater recharge in various situations, which can be summarized for agricultural lands, forest areas and non-forest natural vegetations.

A. Agricultural lands

The dominant type of landuse in The Netherlands is grass-land, also covering the parcels of the ten investigated farms. A comparison of tritium-determined values for groundwater recharge (at p=0.35) and values derived from an estimate of rainfall excess, based on meteorological factors, appeared to be in good agreement (*Table 7.2*). The same conclusion followed from an evaluation of the Venhorst farmland, where maize was cultivated. Also the difference between actual and potential evapotranspiration for the wells of the various monitoring networks in all sand districts has the same order of magnitude of roughly 70 $mm{\cdot}a^{-1}$, both for grassland and arable land. The difference is equal to the estimated reduction in evapotranspiration for agricultural crops growing on GT VI (Werkgroep HELP, 1987).

Hence, the long-term averages of groundwater recharge in agricultural areas may be approximated by an estimate of rainfall excess, based on meteorological data, if no disturbing factors are present, like the occurrence of surficial discharge. Surficial discharge was observed in the analysis of tritium levels in cases where a clay layer is present in the topsoil. Moreover, in areas with shallow groundwater tables, often an upward seepage is expected, in combination with surficial discharge. However, only one tritium profile was observed, indicating upward seepage (Holten). Also in only a few monitoring wells the tritium levels were zero or lower than expected. The wells, where tritium levels were observed, are mostly situated in areas with relatively deep groundwater tables.

The conclusion is that surficial discharge of part of the rainfall excess is only expected in situations with clay layers in the topsoil and in areas with shallow groundwater tables.

With regard to the effect of groundwater depths, a distinction was made on the basis of groundwater levels, represented by the so-called Groundwater Depth Classes (GT), as determined in soil surveys carried out by Stiboka (De Vries and Dennekom,

Table 7.3. The estimated effect of groundwater levels, expressed by Groundwater Depth Classes (GT), on rainfall discharge.

GT	I	II	III	III*	IV	V	V*	VI	VII	VII*
AHL (cm)	<25	<25	<25	25-40	40-80	<25	25-40	40-80	80-140	140-200
ALL (cm)	<50	50-80	80-120	80-120	80-120	120-160	120-160	120-160	160-220	220-280
sf	100%	100%	50%	25%	0%	50%	25%	0%	0%	0%
bf	0%	0%	50%	75%	100%	50%	75%	100%	100%	100%

AHL= average high level;
ALL= average low level;
sf= surficial components (overland flow and interflow);
bf= base flow (groundwater flow).

1993). It is assumed that for the most shallow GT's (I and II), the full rainfall excess is discharged surficially and that at deeper levels (GT IV to VII), the rainfall excess is fully discharged by groundwater. For intermediate levels III; III*; V and V*, the discharge will be partly by surficial (fast) components and partly by a flow via saturated groundwater (base flow). The assumed partition of rainfall excess in fast discharge components and in base flow has been summarized in *Table 7.3*. Detailed investigations concerning the partition over the various discharge components are not available. *Table 7.3* represents a first approach; the resulting amounts of the surficial discharge flows are in agreement with the available observations, as summarized by Thunnissen (1987b).

Further detailing, e.g. in the sense of seasonal fluctuations, was not aimed at. For areas with shallow clay layers in the topsoil, notably the Drenthe boulder clay and the Brabant loam layers, it is assumed (on the basis of tritium interpretations) that the occurrence of surficial discharge will lead to a reduction in groundwater recharge by roughly 50% of the local rainfall excess. The actual magnitude of surficial discharge will depend on the local hydrological situation, but information is lacking for further details.

B. Forest areas
The groundwater recharge in forest areas was investigated in detail for the Veluwe region. The conclusions are not supported by the interpretation of the tritium levels measured in samples from monitoring wells in forest areas in the rest of the country, which are summarized in *Table 7.4*. The various reasons why an interpretation of tritium data of groundwater, sampled from wells in forest areas may yield less reliable results, were discussed previously:

1. The vegetation is not homogeneous in most forest areas, leading to varying values of local groundwater recharge.
2. The groundwater of forest areas may have been subject to open water evaporation before recharge, affecting the tritium levels in an arbitrary way.

The interpretation of tritium data from the wells in other areas, leads to the approach that the conclusions reached for the Veluwe investigations are extrapolated to the rest of the country. Hence, also for the other sandy regions of the Netherlands, it is assumed that:

a. The actual evapotranspiration of forest areas, with a dense tree vegetation, equals, by good approximation, the Penman open water evaporation (E_0).
b. The evapotranspiration of inhomogeneous forests, where lanes and open spaces are present, will be smaller than the Penman open water evaporation. The average actual evapotranspiration is roughly E_a=0.9*E_0, including a possible reduction by soil water deficits.

C. Non-forested natural vegetations
The actual evapotranspiration of natural vegetations, not consisting of forests, can hardly be derived from the detailed investigations, or the regional surveys. The reason is not the inaccuracy of specific investigations, but the wide variety of types and densities of vegetations in areas, denominated by nature reserves. Two landscapes were investigated in more detail: the heather vegetations in the Veluwe region and the dune vegetation near Monster. In both cases, it appeared that the actual evapotranspiration was roughly equal to 0.7*E_0, which is not a surprising result. It could mean that natural vegetations containing many grassy components are subject to a potential evapotranspiration of roughly 0.8*E_0, but that soil water

Table 7.4.. Review of observations from monitoring wells in forest areas

Region	P $m \cdot a^{-1}$	E_o $m \cdot a^{-1}$	I_{tr} $m \cdot a^{-1}$	$P-I_{tr}=E_a$ $m \cdot a^{-1}$	E_a/E_o	Number of obs.
w-drenthe	0.84	0.66	0.36	0.48	0.73	1
fr.wouden	0.84	0.66	0.29	0.65	0.98	2
n-overijssel	0.79	0.66	0.31	0.48	0.73	2
salland	0.79	0.66	0.35	0.44	0.67	3
twente	0.76	0.65	0.39	0.37	0.57	2
achterhoek	0.77	0.67	0.28	0.49	0.73	8
veluwe-lmg	0.88	0.67	0.29	0.59	0.88	6
veluwe-pmg	0.88	0.67	0.28	0.60	0.90	5
utr.h+gooi	0.82	0.67	0.32	0.50	0.75	2
nw-brabant	0.80	0.70	0.28	0.52	0.74	2
kempen	0.75	0.70	0.24	0.51	0.73	2
peel	0.74	0.69	0.37	0.37	0.54	3
md-limburg	0.74	0.70	0.29	0.45	0.64	2

P= observed long-term average rainfall
E_o= long-term average of Penman open water evaporation
I_{tr}= groundwater recharge derived from tritium observations;
E_a= average actual evapotranspiration (= rainfall- groundwater recharge);
number obs.= number of monitoring wells in forest areas with an interpretation;

deficits will cause a reduction of roughly $0.1*E_0$, representing approximately 70 $mm \cdot a^{-1}$. Natural vegetations in the Netherlands at present often will consist of grasses and a reduction of the potential evapotranspiration in the order of magnitude of 70 $mm \cdot a^{-1}$ is a likely value.

7.2.2. Environmental aspects

The investigations at ten grassland farms, dispersed over the Netherlands, were aiming at a determination of the leaching of nitrogen compounds to the soil. The results are summarized in *Table 7.5*. The fertilization of the test farms with nitrogen compounds is slightly more than the average nitrogen dose on grassland in the sandy areas. The average leaching to the saturated groundwater was determined by taking the groundwater recharge determined from the tritium data and multiplying it by the average nitrate concentration measured at shallow boreholes. It follows that the leaching is roughly between 10 and 20% of the dose. The average leaching corresponds to the leaching predicted using stationary models (Van Drecht et al., 1991), including an effect of groundwater depths (Boumans et al., 1989). However, the scattering of individual observations around the mean values is relatively large. Deviations occur at the Veendam farm, possibly explained by the relatively high organic component in the shallow soil and at the Moergestel and Sevenum farms. For the peculiar situation in Moergestel and in Sevenum, a possible explanation related to the meteorological features (frozen soils) in the winter periods, previous to sampling, is offered.

Both the vertical and horizontal components of the groundwater flow patterns on the investigated farms are relatively well known. Also known is the spatial distribution of nitrate concentrations just below the phreatic level. Hence, for each observed nitrate concentration in deeper soil layers, a start value can be estimated, implying that a possible reduction during the flow in deeper groundwater can be estimated. An elaboration is summarized in *Table 7.5*, indicating that the average reduction in the saturated layers is approximately 50%. The variation in the values in the deeper groundwater is again large.

The detailed investigations, especially at the Rips location and in the Vredepeel forest, showed the effects of local differences in vegetation on groundwater composition. Temporal changes in the composition of infiltrating groundwater also became clear from model results (section 2.2.3) and from the Vredepeel observations. In general, inhomogeneities in local recharge areas and temporal fluctuations in the local groundwater flow patterns may cause variations in the groundwater composition. Such deviations may be observed in a series of screens in one well (not only on one date, but also in the course of time) during monitoring of the groundwater composition. Hoogendoorn (1990) reaches a similar conclusion.

The Veluwe investigations showed the relations between the composition of precipitation and the resulting groundwater composition in areas with a natural vegetation not having any chemical compounds applied, except for aerial deposition. Many basic features of the groundwater composition can be derived from rainfall composition (measured in samples from open rainwater collectors) by applying condensation factors estimated from the amounts of rainfall and actual evapotranspiration. For sulphate, an additional input, caused by dry atmospheric deposition, has to be taken into account. The denitrification in forest soils removes roughly 60% of the nitrogen load.

7.3. Mapping of groundwater travel times

7.3.1. Use of Geographical Information Systems (GIS)

The effects of temporal variations in groundwater velocities are absent in deeper layers because the average recharge prevails. However, the spatial variations in the average groundwater recharge can be large and such variations will have an effect on local groundwater ages and on groundwater travel times, also in deeper layers. The average recharge at each specific location in sandy regions will depend on the magnitude of water available for discharge, which is the rainfall excess, locally reduced by overland flow and by interflow. Hence, the factors involved are precipitation, actual evapotranspiration and surficial discharge components. These elements are related to topographical data and to soil and groundwater features of the various sandy regions, which can be represented in a Geographical Information System. A GIS system has been developed (RIVM, 1991) containing the necessary information on soil and groundwater. Within that system, relationships were elaborated in order to determine the groundwater recharge. The elements used:

a. The country is divided in a regular grid of 500*500 m, each grid cell representing 25 ha, geographically defined within the territory of the Netherlands.
b. A grid cell has been assigned the specific distribution of land use types derived from LANDSAT images, which were made available by Thunnissen et al. (1992). Various agricultural crops are distinguished in a dataset. In *Fig.7.6* these are schematized in major categories.
c. The distribution of soil types, based on the 1:250000 Soil Map (De Vries and Dennekom, 1993) is represented in *Fig.7.7* in the form of the major soil types.
d. Groundwater levels, determined within the framework of the 1:50000 Soil Maps by Stiboka (De Vries and Dennekom, 1993), are represented as a distribution of Groundwater Depth Classes (GT). The dominant GT per grid is shown in *Fig.7.5*.
e. The distribution of the long-term averages of precipitation, according to the pattern of *Fig. 3.1* was digitized, such that each grid will obtain, by interpolation, the average amount of precipitation holding for that grid.

Table 7.5. Nitrate leaching at the investigated farms

Location	nitrogen dose $kg.ha^{-1}.a^{-1}$	leaching = %gift	no reduction obs.screens cored drill.	50% red. obs.screens cored drill.	>80% red. obs.screens cored drill.
Veendam	740	8%	20%	20%	40%
Elp	655	16%	15%	25%	20%
Dalen	635	21%	30%	20%	50%
Holten	567	10%	undet.	undet.	undet.
Almen	805	19%	undet.	undet.	undet.
Neede	740	20%	50%	25%	25%
Wanroij	745	14%	33%	33%	33%
Moerg.	730	1.5%	80%	20%	0%
Bavel	760	14%	undet.	undet.	undet.
Sevenum	730	3.6%	100%	0%	0%

f. The pattern of the long-term averages of the reference evaporation, according to *Fig. 3.2*, was also digitized. Each grid obtains, by interpolation, the average amount of the reference evapotranspiration following from the meteorological conditions, determined at the main weather stations and extrapolated to that grid.
g. The occurrence of surficial runoff components was based on the values of GT in the grid cell and the amounts are estimated with the help of *Table 7.3*. In areas where the topsoil contains a shallow clay layer with Groundwater Depth Classes IV, VI and VII, an additional surficial discharge is assumed by stating that 50% of the local rainfall excess is surficially discharged in the areas involved (*Fig.7.8*).
h. The thickness of the aquifer system was defined for each sandy region and values are assigned to all grids (*Fig.7.9*).

7.3.2. Estimating the actual evapotranspiration

The potential evapotranspiration (E_p) for the various types of land use is determined by applying the appropriate crop factors, indicating the relation $E_p=f*E_r$. Crop factors, f, according to CHO-TNO (1987) for agricultural crops and Makkink (1960) for natural vegetations, are averaged for the growing season, resulting in:

grass	$E_p=1.00*E_r$	**beets**	$E_p=0.80*E_r$
maize	$E_p=0.85*E_r$	**dec. forest**	$E_p=1.00*E_r$
cereals	$E_p=0.75*E_r$	**heather etc.**	$E_p=1.00*E_r$
potatoes	$E_p=0.76*E_r$	**pine forest**	$E_p=1.25*E_r$

By combining the data on soil use with crop factors, values of the potential evapotranspirations for each grid can be derived (*Fig.7.9*). The average actual evapotranspiration equals the potential evapotranspiration minus the estimated average water deficits derived from the HELP tables (Werkgroep HELP,1987). The tables are based on soil type and land use, presenting a factor RED, indicating the reduction in evapotranspiration as a percentage of the potential evapotranspiration during the growing season. Hence, for the determination of annual averages, another factor, f_s, has to be introduced (Van Drecht et al., in prep.), which is equal to the ratio $f_s=E_{p,s}$ (growing season) divided by $E_{p,y}$ (full year), assuming the values:

grass	$f_s=0.80$	**beets**	$f_s=0.86$
maize	$f_s=0.81$	**cereals**	$f_s=0.92$
potatoes	$f_s=0.91$	**avg. arable**	$f_s=0.90$

The HELP tables are valid for meteorological conditions valid for De Bilt (the main weather station). Werkgroep HELP (1987) remarked that crop reduction factors (=reduction of potential evapotranspiration) depend on meteorological variations within the Netherlands, leading to modifications. Van Drecht et al. (in prep.) proposes to take into account the regional differences in summer rainfall by equal modifications of the soil water deficits, implying changes of the same magnitude in rainfall excess. Given the above relationships, the average annual soil water deficit, D, can be calculated for each grid (*Fig.7.11*), according to:

$$\mathbf{D=RED*f_s*f*E_r}\ (\mathrm{mm{\cdot}a^{-1}})$$

The actual evapotranspiration equals the potential evapotranspiration minus the deficit (*Fig.7.12*). Rainfall minus actual evapotranspiration is equal to the rainfall excess (*Fig.7.13*) to be discharged by surficial flow and by groundwater. The groundwater recharge at each grid can be estimated if the amount of surficial discharge is known. For sandy areas with a deep groundwater table, surficial discharge components may be ignored and the groundwater recharge is equal to the rainfall excess. From a comparison with tritium-derived values for groundwater recharge (*Table 7.2*), it can be concluded for agricultural areas that the rainfall excess corresponds to the groundwater recharge. For areas with a natural vegetation, the situation is less clear. The actual evapotranspiration in forest areas depends on the tree density. The density of the vegetation is important in other nature reserves not covered by trees. In general, the conclusions of section 7.2 have been applied to natural vegetations.

7.3.3. Groundwater recharge in sandy regions

The average groundwater recharge is the amount of the average precipitation minus the average actual evapotranspiration minus the estimated amounts of the average surficial runoff components. For each grid in the GIS system of the sandy regions, the values of the components determining the average groundwater recharge (GR) can be estimated according to the following procedure:

1. Estimate the rainfall excess ($P-E_a$);
2. Estimate the surficial discharge (SR) in areas with GT I; GT II, GT III; GT III*; GT V and GT V*, according to *Table 7.3*;

3. Estimate the surficial discharge (SR) for areas with GT IV; GT VI; GT VII and GT VII*, and with a clay layer in the topsoil, by assuming that $SR=0.5*(P-E_a)$; SR=0 in areas without a shallow clay layer;
4. Assess the groundwater recharge $GR=P-E_a-SR$.

The results of a determination within the GIS system of the long-term annual averages of the estimated amounts of surficial discharge in the sandy regions are represented in *Fig.7.8.* The average annual groundwater recharge resulting from the values of rainfall excess and the occurrence of surficial discharge in the sandy regions of the Netherlands is depicted in *Fig.7.14.* The accuracy of the average groundwater recharge determined by applying the above estimates will consist of the combined accuracies of the specific determinations, which can be estimated using expert judgment. A distinction has to be made between agricultural areas and areas with a natural vegetation.

For agricultural areas, the inaccuracy of the determination of precipitation will be in the order of magnitude of 10 $mm{\cdot}a^{-1}$ (not taking into account the effect of sprinkling). The inaccuracy of the actual evapotranspiration will estimatedly be 25 $mm{\cdot}a^{-1}$; the estimate of surficial runoff will be relatively inaccurate, maybe amounting to 50 $mm{\cdot}a^{-1}$.

The inaccuracies in the determination of the actual evapotranspiration of areas covered with a natural vegetation are mostly larger than for agricultural areas. Presumably, the inaccuracy will be more than 80 $mm{\cdot}a^{-1}$, but exact values can hardly be estimated; data are lacking for a detailed consideration. A more exact elaboration of inaccuracies in the determination of the groundwater recharge would require the application of a statistical analysis of the contributing factors for which the data are lacking at present.

7.3.4. Groundwater travel times at various levels

The travel times of saturated groundwater in the sandy regions of the Netherlands can be determined according to the regional groundwater flow equation:

$$t_{sat}=pD/I*\ln[D/(D-z)],$$

with: t_{sat}=travel time in the saturated zone (a);
p= porosity, here p=0.35;
D= aquifer thickness (m);
I= groundwater recharge ($m{\cdot}a^{-1}$);
z= depth below pheatic level (m).

For the total travel times of water in the soil, the residence time in the unsaturated zone has to be added to travel times in saturated groundwater. In roughly 90% of the sandy regions, groundwater tables (gwt) will be within a depth of less than 2 m below land surface (TNO, 1986). A good approximation in such cases is that the residence time in the unsaturated soil is equal to one year. Only in the relatively high hills, mostly consisting of ice-pushed ridges, will the groundwater levels be deeper and the residence times larger than one year; the travel times in the unsaturated zone have to be determined for each case. In the Veluwe region, the average downward velocity in the unsaturated zone is roughly 3 $m{\cdot}a^{-1}$ (Appelo and Van Ree, 1983).

The values of the parameters needed for a determination of the groundwater travel times in the saturated soil were given or determined in a GIS environment. Substitution of these values in the above equation will result in a value for t_{sat} for any selected level at depth z in subsurface. Computations were carried out for the levels where the screens of the national and provincial monitoring networks have been installed:

- at a level of gwt-5 m (z=5 m);
- at a level of gwt-10 m (z=10 m);
- at a level of gwt-25 m (z=25 m).

In fact, the monitoring screens were mostly installed at a depth below land surface of the indicated value, but for practical reasons the depth below the groundwater table has been chosen. The results are given in *Figs.7.15* to *7.17.*

On a local scale, differences in vegetation may lead to deviations of the expected age distribution in the soil. Evidently, in many natural situations, variations in land use will be present, although they will not always imply large differences in groundwater recharge. For practical reasons, monitoring wells were often located at the transition between different types of land use. In forest areas, a well was usually placed alongside forest lanes; in agricultural areas they were often situated on the boundary of parcels. Hence, the hydrological situation does not always fully correspond to the predominant type of land use and this may have consequences for the groundwater age determined at the observed well. The indicated groundwater ages are average values, which do not necessarily represent groundwater ages at specific locations.

7.4. Summary of the conclusions

The comparison of time series in rainfall tritium and tritium levels observed in groundwater give cause for

a slight modification of the reference series for rainfall tritium levels used for interpreting groundwater values. The values for the years 1962 to 1966, which were obtained by an extrapolation of the levels measured in the precipitation at Vienna, were reduced by 50%. Presumably, also the regional factors in the years before 1970 will deviate from the values determined for the period after 1970, but data are lacking for a more detailed evaluation. The regional factors derived for the period after 1970 are applied as a first approach for the earlier period:
Conclusion: A reference series for tritium levels in Groningen rainfall is presented in Table 7.1; the regional relationships given in Fig.3.1 are elaborated for the years after 1970. They constitute an acceptable first approach to rainfall data for the earlier period.

The interpretation of the many vertical tritium profiles observed in groundwater of the sandy regions in the Netherlands indicates a continuous downward percolation:
Conclusion: In the Netherlands sandy areas, where groundwater is recharged by the rainfall excess, the planes of constant groundwater age are horizons in the subsurface.

The comparison of tritium-derived values of vertical flow and groundwater recharge determined by other methods resulted in a consistent value for the porosity:
Conclusion: The effective porosity of the shallow subsurface of the sandy regions is close to p=0.35, except for the shallow subsurface of dune areas where it approaches p=0.40.

In the isotope levels of saturated groundwater, including tritium, virtually no seasonal variations can be detected. Other observations also support the assumed mixing in the topsoil on an annual basis:
Conclusion: The recharge of saturated groundwater consists of water which has been mixed, at least annually, in the unsaturated zone.

The great majority of observed tritium levels indicated a coherent groundwater flow pattern, occupying the full Pleistocene aquifer, except in those areas where the Pleistocene sediments contain a relatively thick series of poorly permeable layers. The existence of separate (nested) groundwater flow systems is not supported by investigations in the very large areas, where tritium data are available.
Conclusion: The distinction of superimposed (nested) groundwater flow systems will be of limited use for the sandy areas of the Netherlands.

Although the topography only has a limited influence on groundwater flow, the detailed investigations showed the effects of differences in vegetation on the local groundwater composition. Also, temporary changes in the composition of infiltrating groundwater became clear from model results (section 2.2.3) and from the observations (the Vredepeel example, section 5.4).
Conclusion: The variations in the groundwater composition observed in a series of screens in one well may (on one sampling date, but also in the course of time) be caused by inhomogeneities in the local recharge area and by temporal shifts in the local groundwater flow patterns.

The groundwater recharge in agricultural areas, based on an interpretation of groundwater tritium levels, is in good agreement with values of rainfall excess estimated from meteorological data and taking into account possible soil water deficits resulting from the local soil and groundwater features.
Conclusion: The estimates of rainfall excess, derived from meteorological data in combination with the local soil and groundwater features, form a good basis for estimating groundwater recharge in agricultural areas.

In specific areas, the occurrence of surficial discharge will reduce the amount of water available for groundwater recharge. First estimates for areas with shallow groundwater tables can be derived from Table 7.3. In areas where the shallow soil contains clay or loam layers, hampering the downward percolation of water, an interpretation of groundwater tritium levels results in a possible surficial discharge of roughly 50% of the annual rainfall excess.
Conclusion: In estimating groundwater recharge from rainfall excess, the amounts of surficially discharged water cannot be ignored, but the effects can hardly be generalized.

The groundwater recharge in areas with a natural vegetation will show a wide variation. A working hypothesis, based on a relation with E_o and supported by the interpretation of tritium observations and considerations on groundwater composition in the Veluwe region, is proposed. The general validity of the assumed relationships with the open water evapotranspiration for areas with a natural vegetation needs to be investigated in more detail.
Conclusion: A satisfactory first approach for areas with a natural vegetation is based on the actual evapotranspiration being related to the reference evaporation by vegetation factors, which are $E_p=1.0*E_o$ for pine forests and $E_p=0.8\ E_o$ for heathlands, natural dune vegetations and deciduous forest. Locally, strong deviations from these relations may occur. The actual evapotranspiration also depends on possible soil water deficits.

Based on the interpretation of tritium data, values of the groundwater recharge can be assessed for the full area of the sandy regions using land-use data, meteorological factors and soil features. The vertical groundwater velocity is initiated by groundwater recharge, implying that the groundwater travel times can also be calculated for the sandy regions of the Netherlands. Differences in groundwater recharge, but also in the geohydrological situation, will lead to differences in groundwater travel times. Especially at deeper soil layers, the aquifer depth becomes a predominant factor.

Conclusion: A coherent mapping of groundwater travel times in the sandy regions of the Netherlands is only possible with data on the local groundwater recharge and the local geohydrological situation, as investigated in the present study.

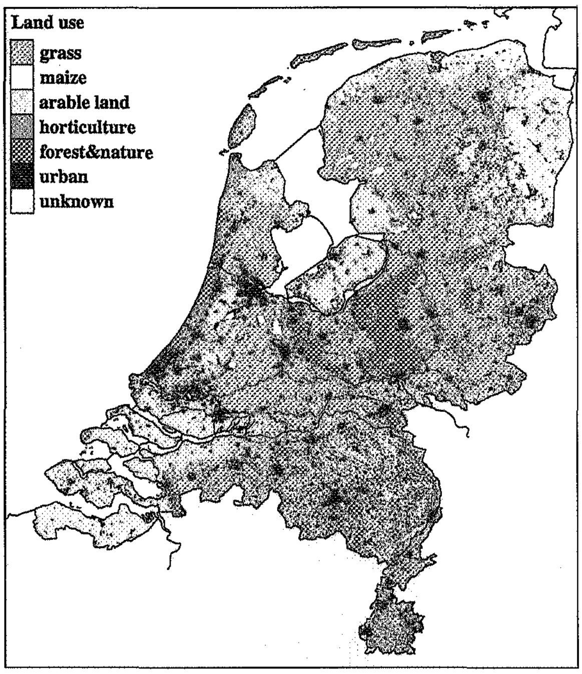


Fig. 7.6. Soil use, acc. to (Thunnissen, 1992).

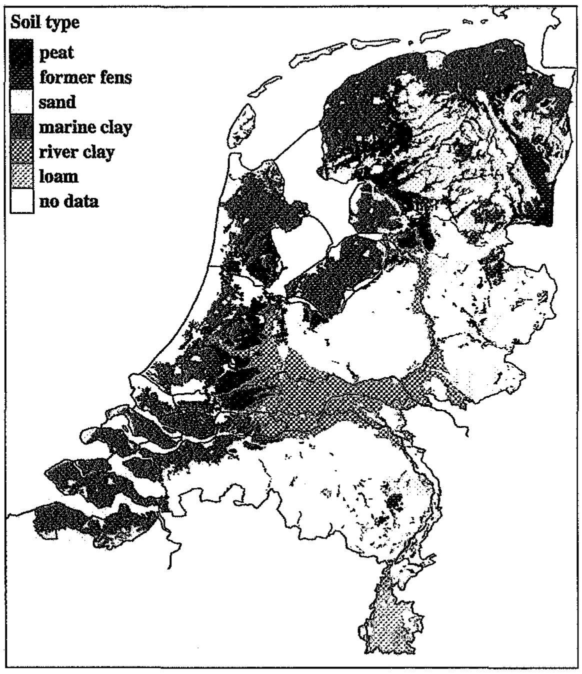


Fig. 7.7. Predominant soil types acc. to (Vries, 1993).

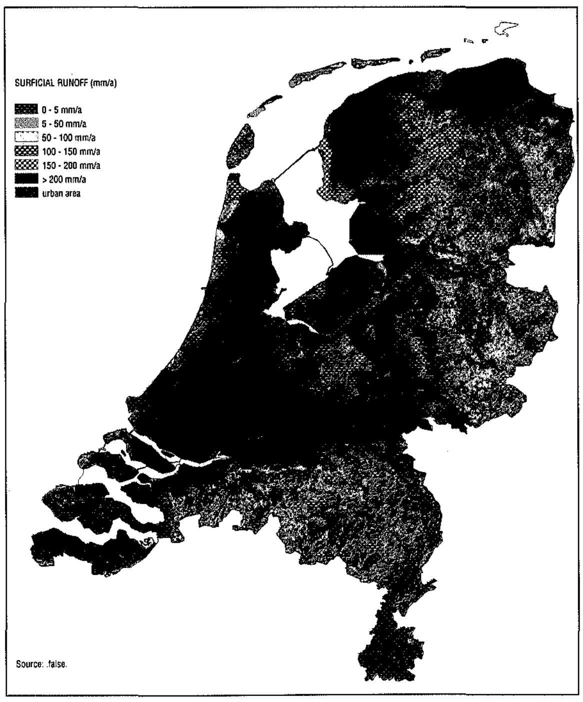


Fig. 7.8. An estimate of surficial discharge in sandy areas.

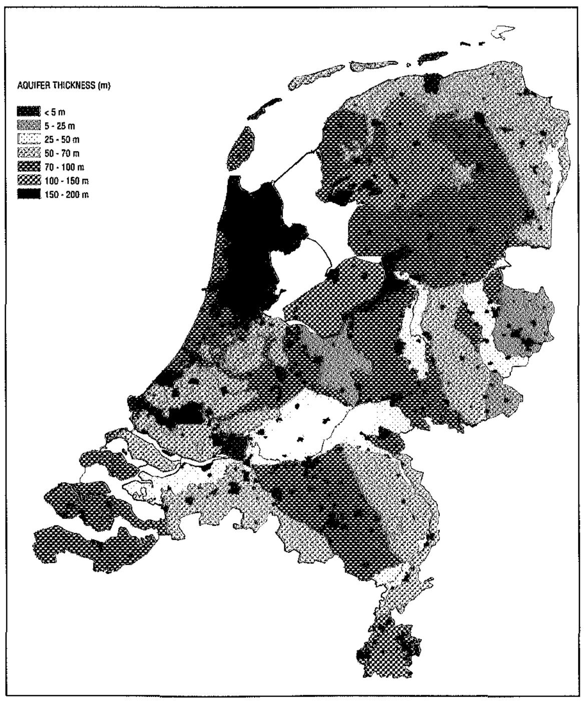


Fig. 7.9. Aquifer thickness.

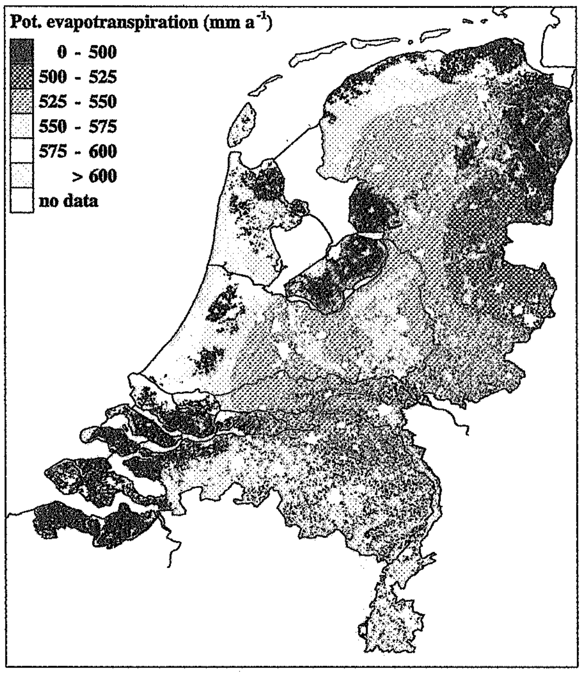


Fig. 7.10. The average potential evapotranspiration.

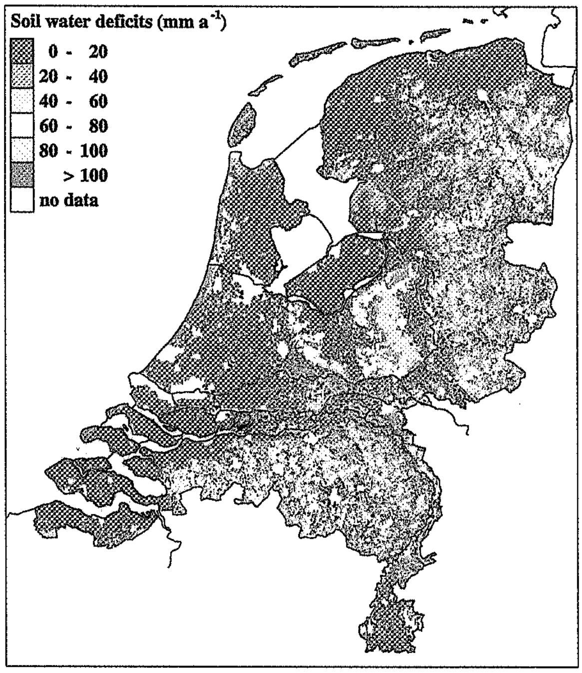


Fig. 7.11. Crop evapotranspiration deficit over 1960-1990.

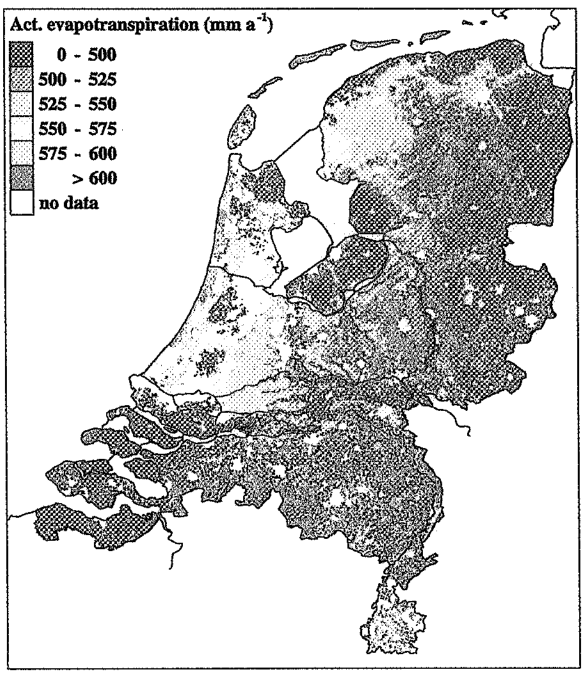


Fig. 7.12. Actual evapotranspiration in the period 1960-1990.

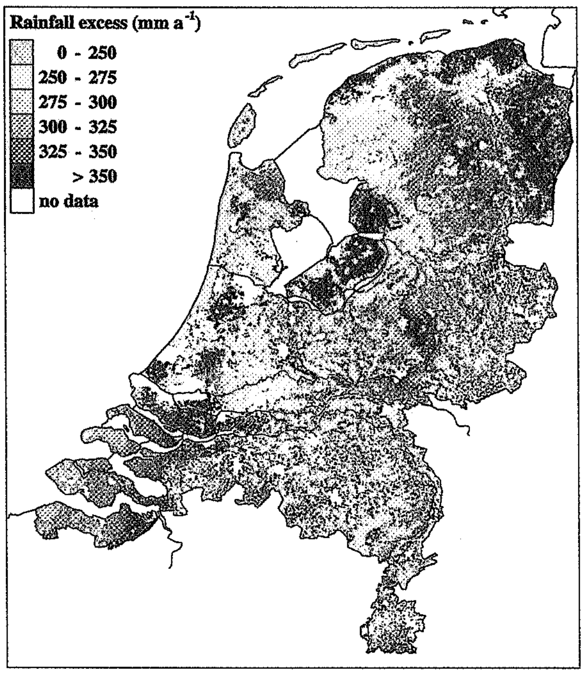


Fig. 7.13. The rainfall excess over the period 1960-1990.

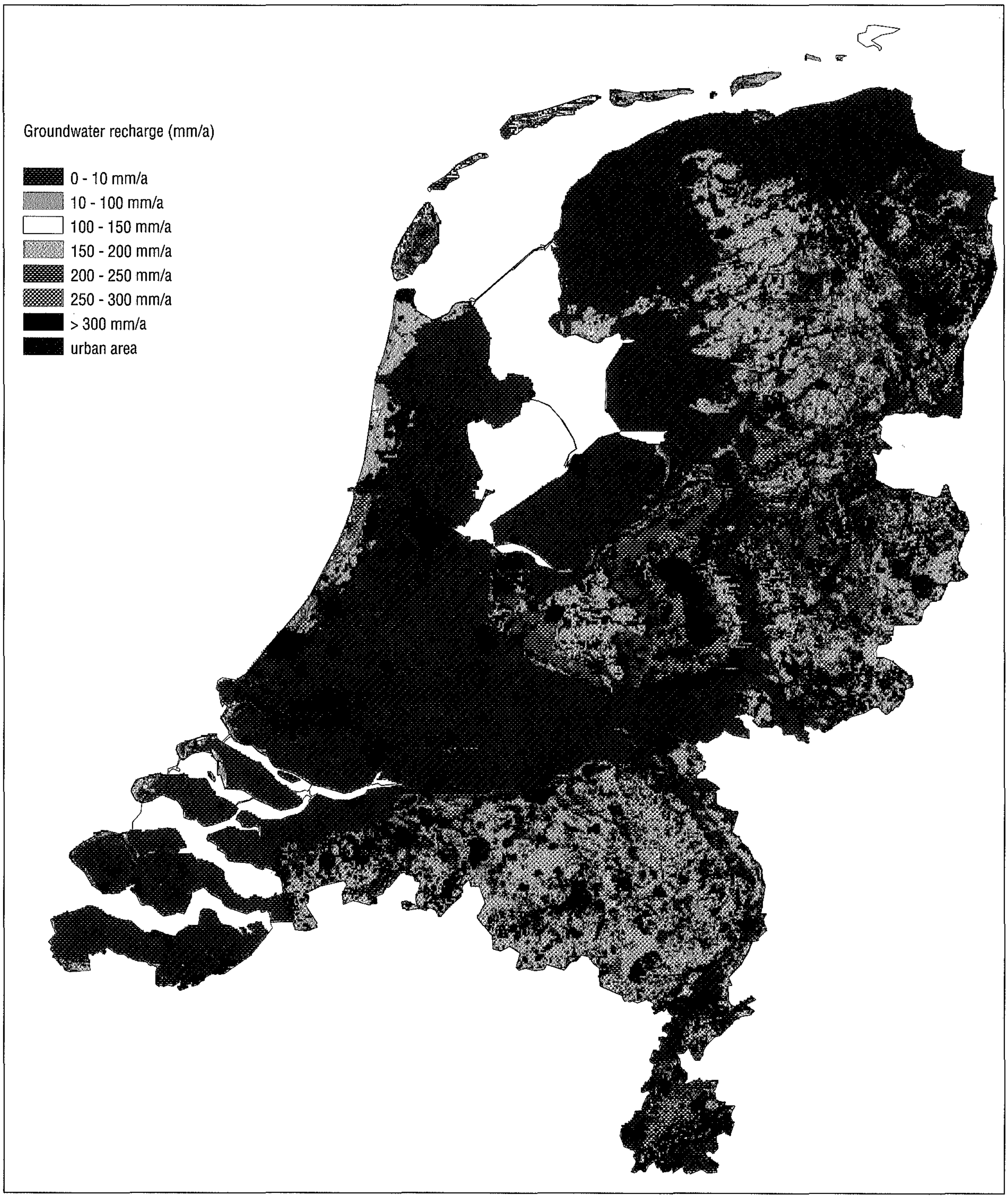


Fig. 7.14. An estimate of the groundwater recharge in sandy areas.

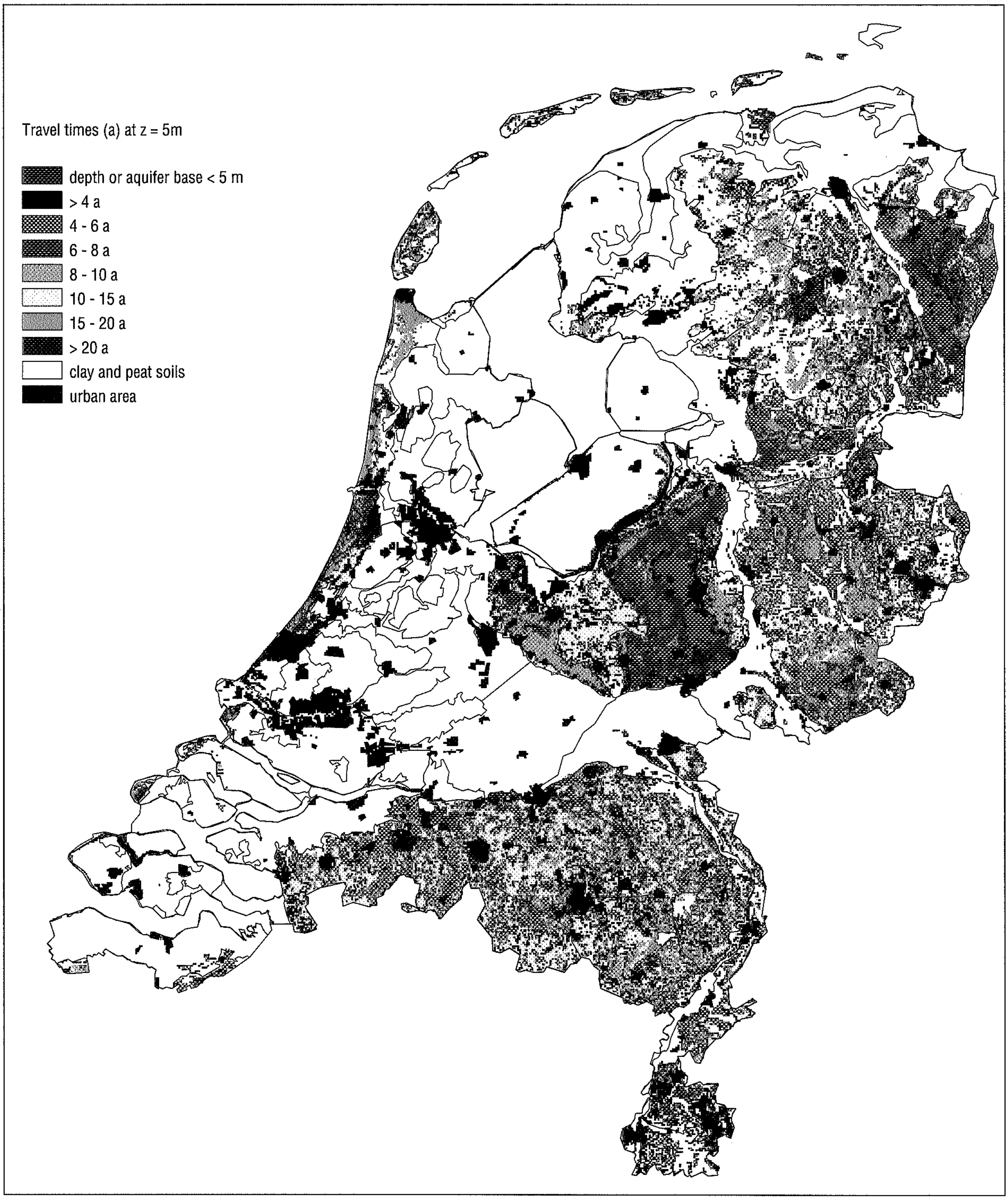


Fig. 7.15. Travel times in saturated groundwater at GWT-5 m.

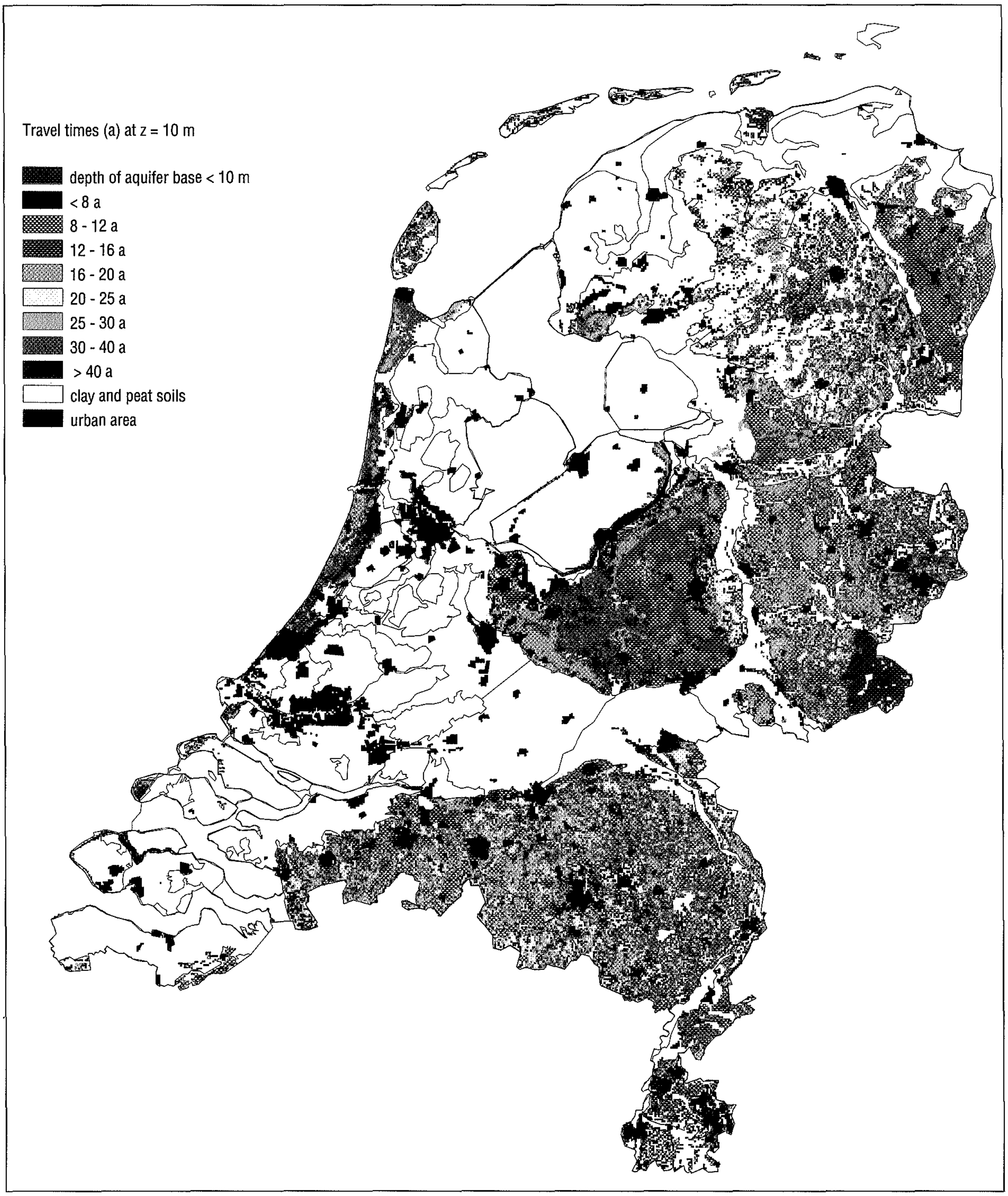


Fig. 7.16. Travel times in saturated groundwater at GWT-10 m.

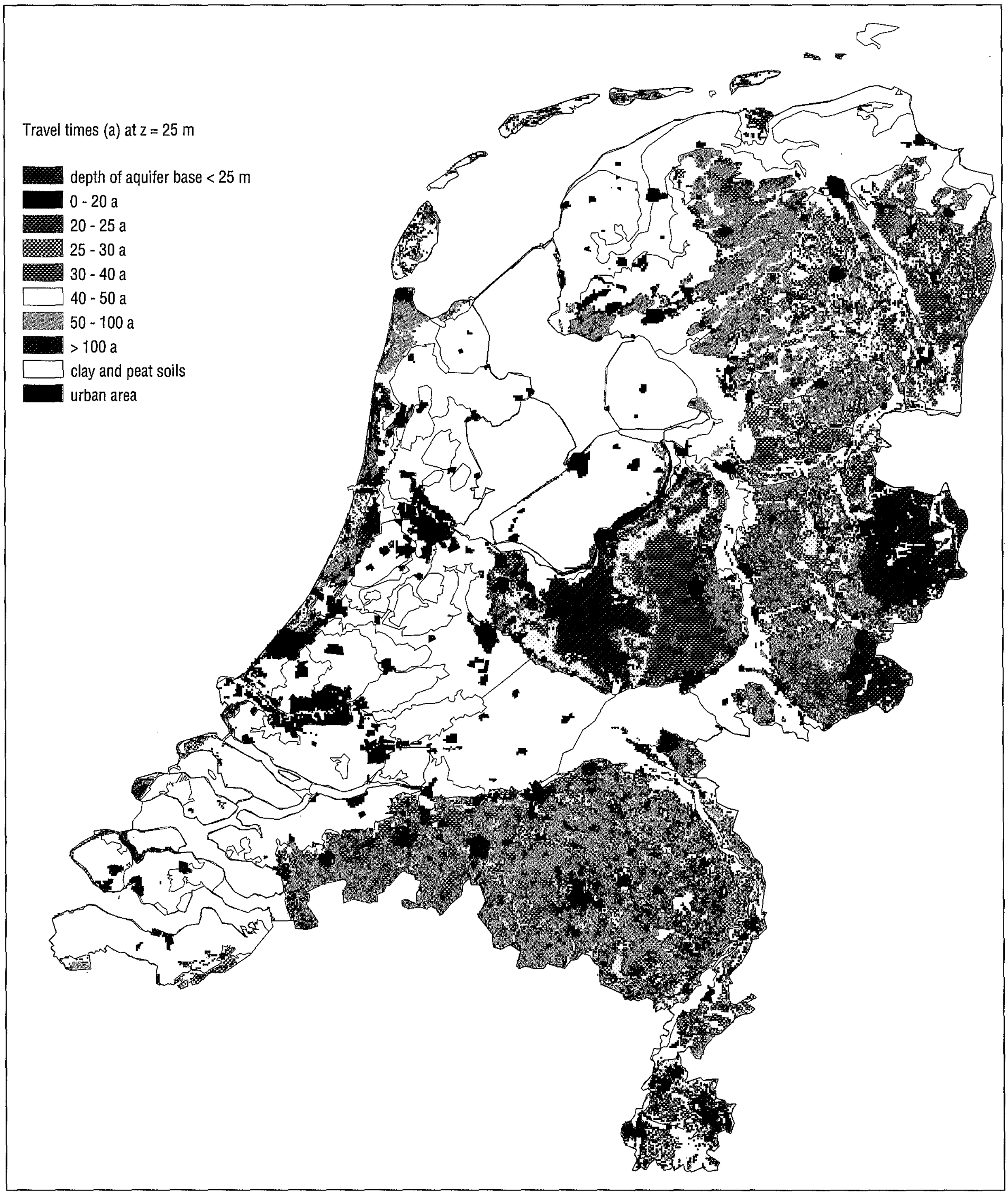


Fig. 7.17. Travel times in saturated groundwater at GWT-25 m.

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About the author:

Cornelis Roelf Meinardi was born in Groningen in 1942. He spent his youth on a farm in the northern part of the Netherlands, near the coast of the Wadden Sea. In the 1960s he studied at Delft Technical University, graduating in 1969 as a Dutch civil engineer. In the same year he was employed as a hydrologist by the National Institute for Water Supply, RID, incorporated in the National Institute of Public Health and Environmental Protection, RIVM in 1984. Apart from his work in the field of environmental soil problems, a considerable share of his activities has consisted of assisting in projects on the water supply of developing countries.

Abstact:

A major environmental problem in the Netherlands is the current deterioration of soil quality due to a complexity of human activities. Part of the problem consists of further transport into the soil of pollutants, which are carried along by the flow of groundwater. The vertical flow in subsurface layers is especially important in cases of diffuse contamination. Groundwater flow in the sandy regions of the Netherlands is initiated by a groundwater recharge derived from excess rainfall. The travel times of groundwater constitute an essential feature of the flow. Groundwater recharge and travel times are elaborated in this thesis. The study of shallow groundwater conditions was based on a hierarchy of investigations, the foundation of which consists of detailed investigations at a large number of locations dispersed over the sandy regions of the Netherlands. A main element of the fieldwork was the analyses of the tritium levels in groundwater, aimed at dating the samples. The local results were integrated in regional overviews and ultimately in a national mapping of the groundwater recharge and travel times at three depths (5, 10 and 25 m below the groundwater table). The final results were achieved through Geographical Information System (GIS) methods.